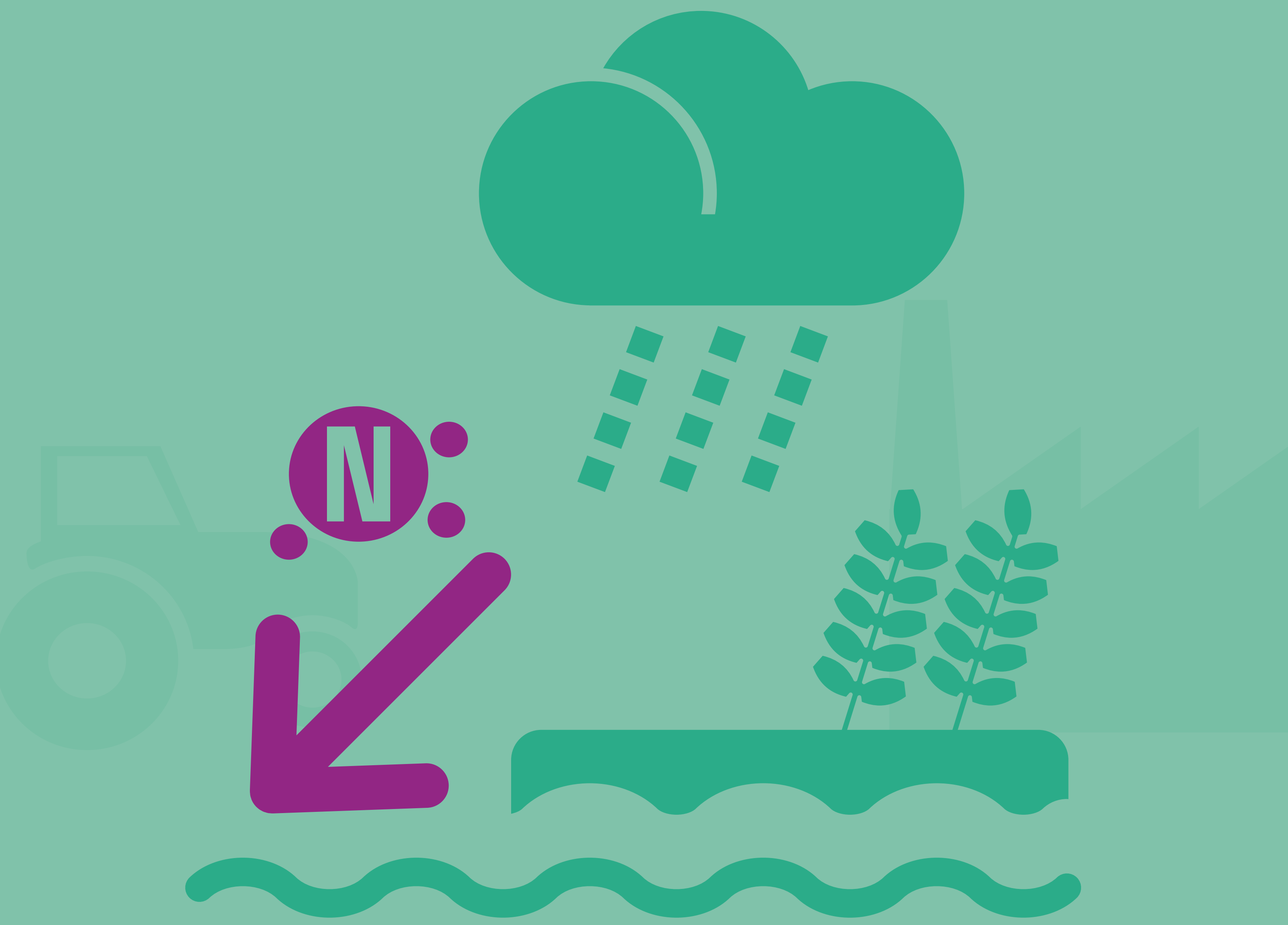
Contributions of emissions from different countries and sectors to atmospheric nitrogen input to the Baltic Sea and its sub-basins

Baltic Marine Environment Protection Commission

Nutrient inputs

2024



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Contents

1. Introduction

Nitrogen deposition to the nine sub-basins of the Baltic Sea, along with source-receptor relationships quantifying airborne nitrogen inputs from different countries, are calculated annually by the EMEP Centre MSC-W within the frame of our routine work for HELCOM (see Gauss et al., 2023, for the latest results on airborne nitrogen deposition in 2021).

In this report, additional calculations on sector level are presented, identifying the main contributing emission sectors to nitrogen deposition in the Baltic Sea in the year 2021. The input data and the computational methods are described, and an overview of results is provided in the form of tables and diagrams.

More comprehensive data tables, containing the entire source-receptor matrices, are provided separately in Excel format. The spatially gridded data sets (maps) are saved on EMEP MSC-W's long-term disk storage facilities in netCDF format and can be made available on request.

2. Model setup and calculations

All calculations in this study have been performed with the EMEP MSC-W air quality model. This chapter briefly introduces this model, the experimental setup, and the input data used in this study.

2.1 The EMEP MSC-W model

The EMEP MSC-W model is a multi-pollutant 3D Eulerian Chemical Transport Model and has been used for all nitrogen computations presented here. The model takes into account processes of emissions, advection, turbulent diffusion, chemical transformations, wet and dry depositions and inflow/outflow of pollutants into/out of the model domain. It is documented in detail in Simpson et al. (2012) and the annual chapters on model updates in the EMEP status reports (see Simpson et al., 2021; 2022; 2023, and references therein, for the latest updates).

The model is regularly evaluated against measurements from the EMEP network under the LRTAP Convention (https://aeroval.met.no/evaluation.php?project=emep), but also in a large number of international research projects and operational services, for example in the Copernicus Atmosphere Monitoring Service (CAMS), where evaluation graphs are updated every day, and detailed reports are issued on a quarterly basis (https://atmosphere.copernicus.eu/regional-services).

As in every atmospheric composition model, deviations between model and observations do occur, highly variable both in space and time. These are subject to continuous investigation and result in further development and modifications of the model and the input data used. Nevertheless, the performance of the EMEP MSC-W model can be considered as state-of-the-art over a large range of both gaseous species and particulate matter. The transparency of EMEP model results and activities is further ensured by the availability of the EMEP model code as Open Source at the *github* repository (https://github.com/metno/emep-ctm). In this way, the scientific community as well as advanced policy users can check and apply the model themselves, both as a research tool and to underpin air quality legislation.

The EMEP MSC-W model version rv5.0 has been used for the deposition calculations presented here. This is the same version as was used for the EMEP Status report 2023 (EMEP, 2023) and in the routine work for HELCOM (Gauss et al., 2023).

2.2 Emission data

2.2.1 Source regions

As in the previous project of this kind (Gauss et al., 2020), thirteen source countries/regions have been considered:

- The nine HELCOM countries;
- the sum of all EU countries that are not parties to HELCOM;
- ship traffic in the North Sea (**NOS**);
- ship traffic in the Baltic Sea (**BAS**);
- the rest of the world.

The nine HELCOM countries are Denmark (**DK**), Estonia (**EE**), Finland (**FI**), Germany (**DE**), Latvia (**LV**), Lithuania (**LT**), Poland (**PL**), the Russian Federation (**RU**)*, and Sweden (**SE**). In the remainder of this report, HELCOM countries will be referred to by their 2-letter abbreviation but in lists be sorted alphabetically by their full name.

EU countries that are not parties to HELCOM are labelled '**EUnonHel**' in this study and include Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, France, Greece, Hungary, Ireland, Italy, Luxemburg, Malta, Netherlands, Portugal, Romania, Spain, Slovakia, and Slovenia.

Countries and areas not listed above are combined in '**RoEMEP**' (=rest of the EMEP model domain) in this study and include Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Georgia, Iceland, Kazakhstan, Kyrgyzstan, Moldova, Montenegro, North Africa*, North Macedonia, Norway, Serbia, Switzerland, Tajikistan, Turkey, Turkmenistan, Ukraine, United Kingdom, Uzbekistan, Aral Lake, Black Sea, Caspian Sea, Mediterranean Sea, North Atlantic Ocean*, and Remaining Asian areas*.

One important change since Gauss et al. (2020) is that the United Kingdom is now part of 'RoEMEP' rather than 'EUnonHel'. This must be kept in mind when judging the importance of these source groups in 2021 compared to the results we had published for 2017.

Latest emission data for the year 2021 were obtained in June 2023 from the EMEP Centre CEIP and are listed in the EMEP Status report 1/2023 (EMEP, 2023, their Table A:1). These emissions have been used in our calculations for this project for all land areas throughout the EMEP model domain (displayed in Section 2.3, Fig. 4). The emission data are publicly available at the *WebDab Emission database* at https://ceip.at (see under "Emissions as used in EMEP models" there).

2.2.2 Emission Sectors

Since 2017, emission data provided by EMEP Parties to the Convention via the EMEP Centre CEIP are categorized based on the GNFR system (**G**ridded **N**omenclature **F**or **R**eporting). The 13 main GNFR sectors and how these were combined into the sectors requested in the contract for this project are shown in Table 1. More detail on how GNFR (and the underlying NFR sector emissions) are grouped is given in the Reporting Guidelines of CEIP (CEIP, 2019), and in particular in their Annex 1.

The calculations for this study consider the following five emission sectors:

- 'AGR': Agriculture
- 'TRA': Transport (aviation landing/take-off, road traffic and offroad traffic, inland shipping)
- 'POW': Power (including mainly combustion, but also other processes)
- 'OSC': Other stationary combustion (i.e. stationary combustion other than power generation)
- 'OTH': All other sources (this also includes some combustion from industry)

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* Countries and areas marked by star are not fully included in the EMEP model domain (shown in Section 2.3, Fig. 4). Only emissions within the EMEP model domain are included in the model calculations. However, the contributions to nitrogen depositions to the Baltic Sea from countries and areas outside the EMEP model domain, although very small, are taken into account through the lateral boundary conditions in the model.

GNFR sectors	Simplified sectors used in this study
GNFR_A : Public Power	→ **Power ('POW')**
GNFR_C : Other Stationary Combustion	→ **Other Stationary Combustion ('OSC')**
GNFR_F : Road Transport	→ **Transport ('TRA')**
GNFR_G : Shipping	
GNFR_H : Aviation	
GNFR_I : Offroad	
GNFR_K : Agriculture Livestock	→ **Agriculture ('AGR')**
GNFR_L : Agriculture Other	
GNFR_B : Industry	→ **Other ('OTH')**
GNFR_D : Fugitive	
GNFR_E : Solvents	
GNFR_J : Waste	
GNFR_M : Other	

Table 1. GNFR sectors (left column) used for emission reporting in the EMEP programme, and how these have been combined into simplified sectors (right column).

International shipping is not included in the reports from EMEP parties but is added to the 'Transport' sector in our calculations. We use the CAMS-GLOB-SHIP data set for 2021 (Denier van der Gon et al., 2023, their chapter 4), which is based on the STEAM model version 4.3 developed at the Finnish Meteorological Institute (Jalkanen et al., 2009, 2016; Johannson et al., 2017) and processed for use in EMEP models by the EMEP emission centre CEIP. These emission data are publicly available as well (*WebDab Emission database* at https://ceip.at, see "Emissions as used in EMEP models").

Figures 1 and 2 show the percentage contributions from different sectors to emissions of oxidized and reduced nitrogen emissions, respectively, within each of the nine HELCOM countries. There are clear differences between countries, but Transport (TRA) is the single largest contribution in all countries for oxidized nitrogen, while Agriculture (AGR) is the most dominant sector in all countries for reduced nitrogen. This will be reflected in the source-receptor results presented in Chapter 3.

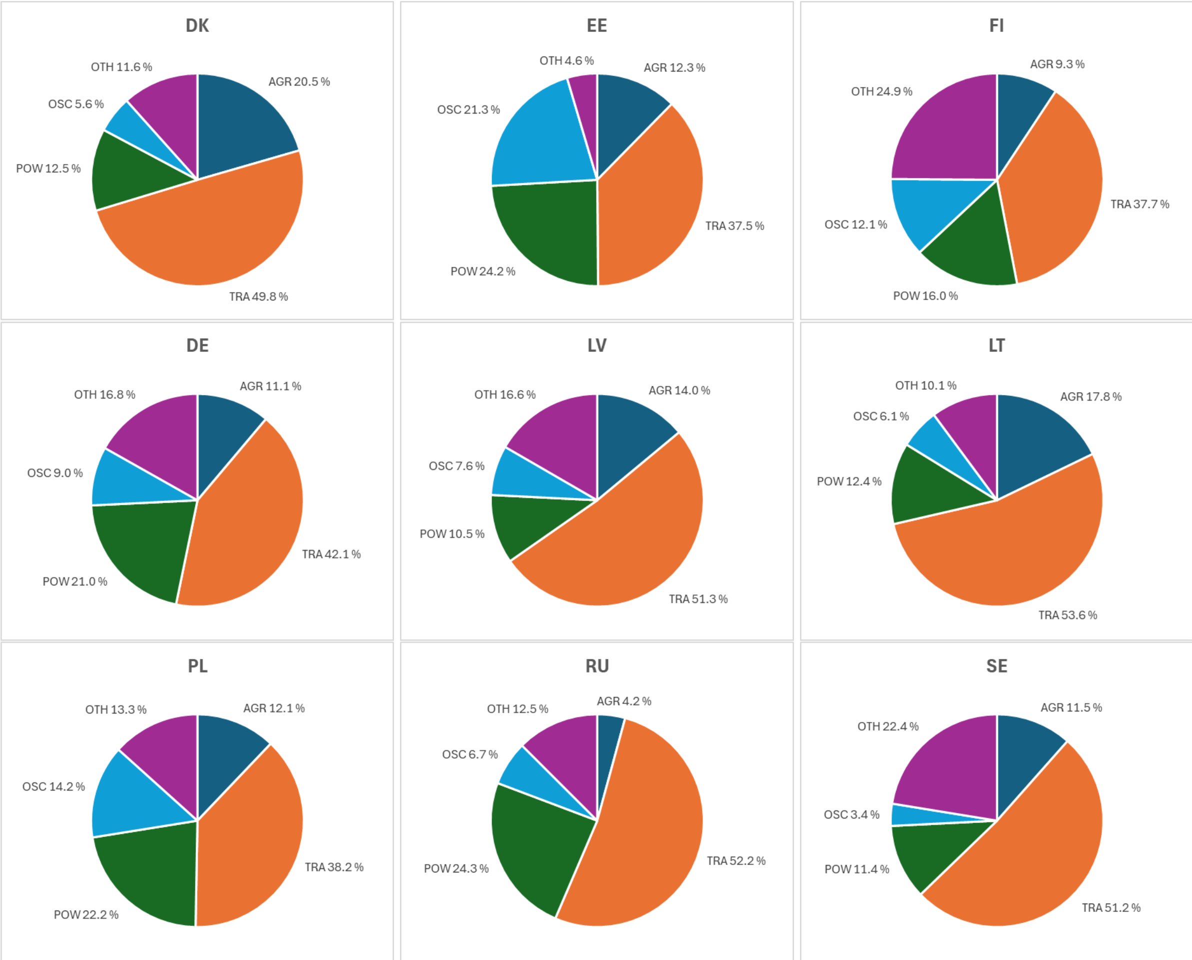

Figure 1. Percentage contributions from different sectors to total emissions of oxidized nitrogen (NOx) in each of the nine HELCOM countries in 2021. For sector abbreviations see Table 1.

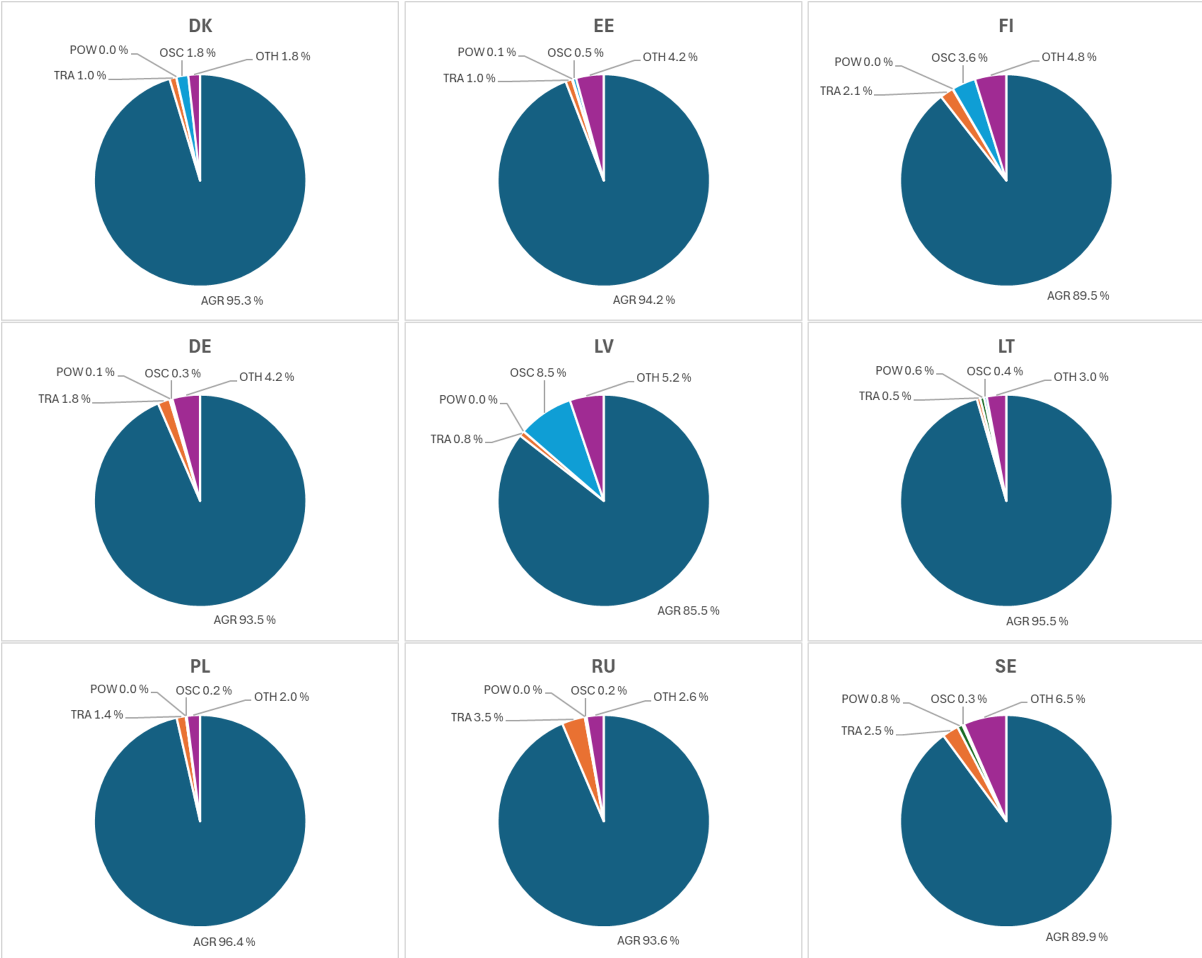

Figure 2. Percentage contributions from different sectors to total emissions of reduced nitrogen (NH_3) in each of the nine HELCOM countries in 2021. For sector abbreviations see Table 1.

In this context it may be interesting to note that NOx emissions from the transport sector are decreasing due to the gradual electrification of road traffic (EEA, 2023), a trend that is expected to continue in the future (Z. Klimont/International Institute for Applied Systems Analysis (IIASA), pers. comm., 2024). At the same time, the production of energy to drive electric vehicles will cause emissions from the Power sector (to the extent this energy is not produced from renewable sources). The contribution from the transport sector will thus decrease in absolute terms, and likely also in its percentage share within the total country emissions.

2.2.3 Emission totals and spatial distribution

The emission totals for 2021 are listed in Tables 2 and 3 for oxidized and reduced nitrogen, respectively, for each of the nine HELCOM countries and the five emission sectors considered in this study. The tables also show the required percentage reductions with respect to 2005 values (according to the Gothenburg Protocol) and whether the commitments have been achieved. Poland, as a member of the EU, is subject to the NEC Directive, according to which it is to reduce its NOx emissions by 30% and its NH_3 emissions by 1% (both commitments were achieved by 2021). Only HELCOM parties are included in the Tables. Other countries that did not fulfil their Gothenburg Protocol commitment by 2021 are Romania (for NOx), as well as Bulgaria, Luxembourg, Norway and Portugal (for NH_3).

In Figure 3, the distribution of nitrogen emissions is shown, clearly reflecting major population centres and, in the case of NOx emissions, also ship tracks in maritime regions. Reduced nitrogen is not emitted from sea areas. NOx emissions from international shipping are not listed in the table, but amount to 171.1 ktonnes(N)/year for the North Sea and 81.6 ktonnes(N)/year for the Baltic Sea. They are included in the Transport (TRA) sector in the source-receptor calculations presented in Chapter 3.

	DK	EE	FI	DE	LV	LT	PL	RU*	SE
AGR	5.6	0.8	3.0	32.9	1.4	2.8	21.8	41.7	4.0
TRA	13.5	2.6	12.0	124	5.3	8.5	68.7	515	18.0
POW	3.4	1.7	5.1	61.9	1.1	2.0	39.9	240	4.0
OSC	1.5	1.5	3.9	26.4	0.8	1.0	25.5	66.6	1.2
OTH	3.2	0.3	8.0	49.6	1.7	1.6	24.0	123	7.9
TOT	27.2	6.9	32.0	295	10.3	15.8	180	987	35.0
Commitment	-56	-18	-35	-39	-32	-48	(-30)	-	-36
Actual	-60	-51	-52	-42	-33	-24	(-31)	(-10)	-44
Compliance	Y	Y	Y	Y	Y	N	(Y)	-	Y

Table 2. Upper 6 rows: Emissions of oxidized nitrogen (NOx) in 2021 within the five sectors defined for this study, as well as the country total, from each of the nine HELCOM parties. Unit: ktonnes(N)/year. For sector abbreviations see Table 1. Lower 3 rows: 'Commitment': Percentual change in emissions with respect to 2005 values required by the Gothenburg Protocol, 'Actual': Percentual change in emissions achieved between 2005 and 2021, 'Compliance': Has the commitment been fulfilled (Yes or No)? Poland and Russia have not ratified the Gothenburg Protocol. For Poland, information is given in relation to the EU NEC Directive.

	DK	EE	FI	DE	LV	LT	PL	RU*	SE
AGR	55.6	7.5	22.9	397	11.0	30.0	230	971	37.8
TRA	0.6	0.1	0.5	7.7	0.1	0.2	3.3	36.5	1.0
POW	0.0	0.0	0.0	0.5	0.0	0.2	0.0	0.5	0.3
OSC	1.1	0.0	0.9	1.3	1.1	0.1	0.4	2.4	0.1
OTH	1.0	0.3	1.2	18.0	0.7	0.9	4.8	26.9	2.7
TOT	58.3	8.0	25.6	425	12.9	31.4	238	1037	42.0
Commitment	-24	-1	-20	-5	-1	-10	(-1)	-	-15
Actual	-23.9	-2	-22	-16	+4	-2	(-11)	(-0)	-11
Compliance	N	Y	Y	Y	N	N	(Y)	-	N

Table 3. Same as Table 2, but for NH_3.

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*) Note that for the Russian Federation (RU), the emission totals listed here apply to the part of the country that is included in the EMEP model domain (shown in Section 2.3, Fig. 4).

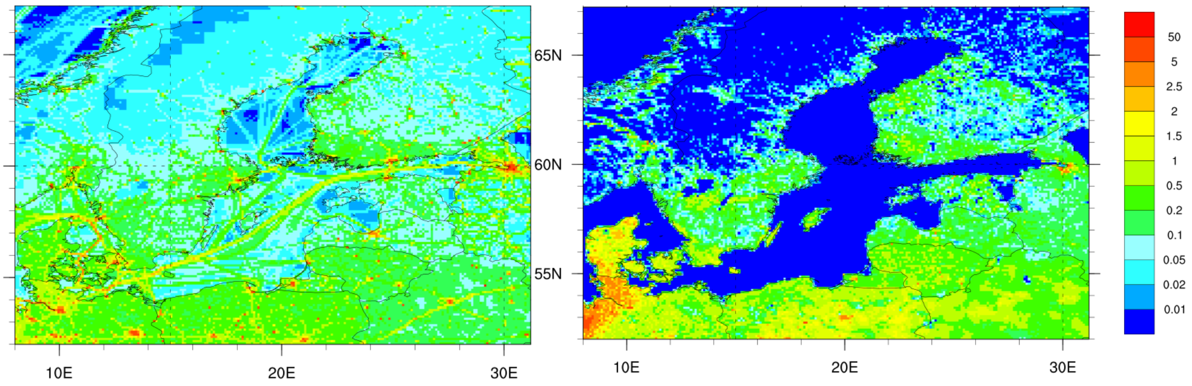


Figure 3. Maps of annual emissions of nitrogen oxides (NOx, left) and ammonia (NH_3, right) in the Baltic Sea region in the year 2021, as provided by CEIP for use in the EMEP MSC-W model. Unit: tonnes(N) km^{-2} yr^{-1}.

2.3 Computational methods

There are different methods to calculate source-receptor relationships (i.e. the contributions from different sources to concentrations and depositions of air pollutants in a given receptor area). For this study, as in all other studies of this type that have been done for HELCOM until now, we have used a kind of perturbation method:

First, a so-called *base run* is performed (for 2021), where all emissions are included in full. This simulation is to reproduce the real situation in 2021 as closely as possible. In the following *perturbation runs*, the emission of one pollutant from one source is reduced by 15% in the model, and the result is compared to the base run in order to assess the importance of the pollutant and the source that has been perturbed. The choice of reducing by 15% is based on many years of experience and is a compromise between staying within the linear regime of atmospheric chemistry (infinitesimal perturbations) and getting a good signal-to-noise ratio. The difference in nitrogen deposition in comparison to the base run is then scaled to 100% by multiplying it by 100/15 to get an estimate of the *total* contribution from the emission source that has been perturbed. This calculation has to be done for all the *5* main pollutants (SOx, NOx, NH_3, VOC, PM), all the *13* considered sources and the 5 sectors, so in theory we would need to perform 5 × 13 × 5 = 325 model simulations, in addition to the base run mentioned above. However, 42 simulations can be omitted: The regions BAS and NOS (Baltic Sea and North Sea) only emit from the Transport sector, and they do not emit reduced nitrogen.

Nevertheless, more than 280 model simulations had to be performed. For this project we could make use of the High Performance Computing system Atos, hosted by ECMWF in Bologna. Therefore, it was decided to perform the source-receptor calculations in 0.3° (lon) × 0.2° (lat) resolution (rather than the coarser 50 × 50 km^2 polar-stereographic grid, which was used in the previous project of this kind, see Gauss et al., 2020). The 0.3° × 0.2° grid is the same as used for the SR calculations for the EMEP status report (EMEP, 2023) and the HELCOM routine work (Gauss et al., 2023). Figure 4 shows the EMEP model domain covered by this grid.

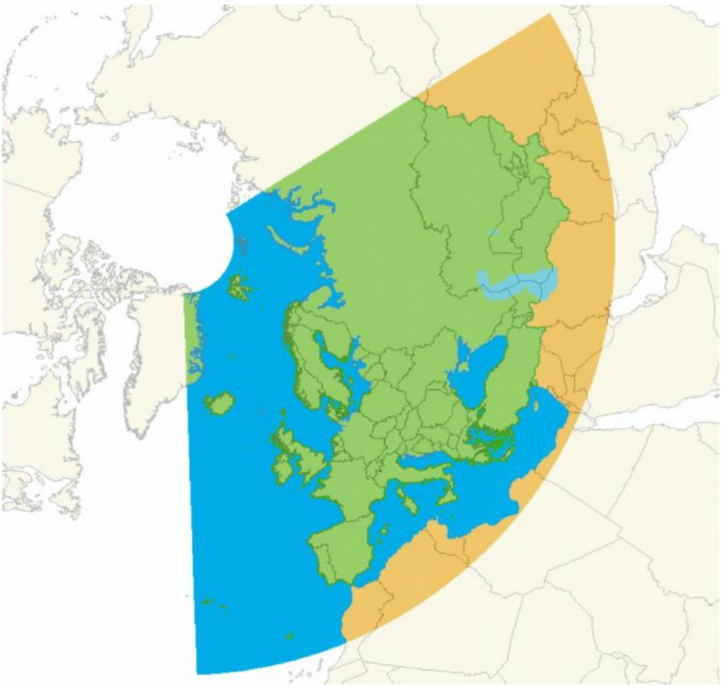


Figure 4. Geographic domain used in the EMEP model calculations. (green: EMEP contracting parties, orange: other countries areas, blue: marine areas)

The definitions of the nine sub-basins considered in this study are listed in Table 4 and visualized in Figure 5.

The meteorological data used in this study have been generated by EMEP MSC-W by running the ECMWF IFS model cycle 46r1 (see ECMWF model documentation).

Contributions to nitrogen deposition in the Baltic Sea depend on meteorological conditions, and these vary from year to year. For this project we decided to use 2021 meteorology and to scale the contributions to the *actual* total deposition calculated for 2021 in 2023 (Gauss et al., 2023). An alternative approach would have been to scale to the *normalized* deposition, i.e. the results obtained in (Gauss et al., 2023) when using 2021 emissions but *average* weather (based on a method described detail in Appendix D of Bartnicki et al. (2017)). However, this could mislead users of the data to believe that we have calculated normalized contributions from individual sectors, which is not the case. The normalized deposition was calculated by Gauss et al. (2023) for country contributions only, but not for sector contributions.

The sum of the contributions presented in this report (and in the accompanying Excel table) thus matches the total actual deposition in 2021 in the Baltic Sea (as calculated in the routine work in 2023), which is 100.6 ktonnes(N), 90.5 ktonnes(N), and 191.1 ktonnes(N) for oxidized, reduced and total nitrogen, respectively.

Without scaling, the sum of contributions would have been 97.9 ktonnes(N), 87.2 ktonnes(N) re-N, and 185.1 ktonnes(N) for oxidized, reduced and total nitrogen respectively. The effect of the scaling is thus well below 5%. The reason why these numbers differ at all is due to remaining non-linearities in atmospheric chemistry (the sum of contributions is not exactly equal to the total deposition) and the fact that the actual deposition calculated in the routine work in 2021 is diagnosed in a model simulation at 0.1 x 0.1 degree simulation, while the contributions in this study were calculated in a coarser (0.3 x 0.2 degree) grid.

Sub-basin	Abbreviation	Area
Archipelago Sea	ARC	13405
Baltic Proper	BAP	209258
Bothnian Bay	BOB	36249
Bothnian Sea	BOS	65397
Gulf of Finland	GUF	29998
Gulf of Riga	GUR	18646
Kattegat	KAT	23659
The Sound	SOU	2328
Western Baltic	WEB	18647
Baltic Sea basin	**BAS**	**417587**

Table 4. The nine sub-basins of the Baltic Sea used for computing depositions, with abbreviations used in this report and areas given in km^2.

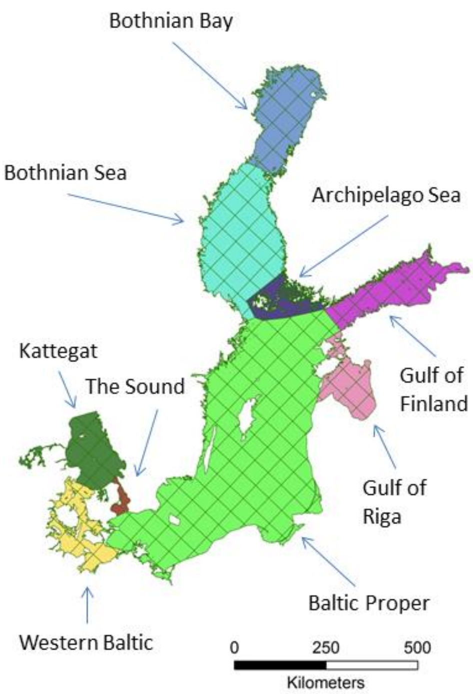


Figure 5. Locations of the sub-basins of the Baltic Sea listed in Table 4 and used for all nitrogen deposition calculations presented in this report. The original figure with the sub-basins was provided by the Baltic Nest Institute (BNI).

2.4 A note on transfer coefficients

When considering source-receptor relationships, an interesting question is how much of each country's emission to the atmosphere is deposited to the Baltic Sea. This percentage is represented by the so-called *transfer coefficients*, which in the context of this report are the factors by which a country's total emission has to be multiplied in order to obtain the country's contribution to atmospheric nitrogen deposition to the Baltic Sea. Transfer coefficients are calculated routinely each year by EMEP MSC-W for the HELCOM countries and the Baltic Sea and are listed in Table 5. They tend to be larger for sources that are close to the Baltic Sea or located upwind of it, or both. However, there are several additional factors that determine the exact magnitude of transfer coefficients, such has meteorological conditions, the chemical lifetime of the species, and the location of emission sources with respect to receptor areas. For example, *reduced* nitrogen emitted several tens of kilometers away (and upwind) from the coast will have a smaller chance of being deposited to the sea than *oxidized* nitrogen because the latter has a longer chemical lifetime. However, if the emission source is located near the coast, the difference in lifetime may not have a noticeable effect because both reduced and oxidized nitrogen will be deposited to the sea located just downwind of the emission source. Indeed, if the adjacent sea area is narrow, e.g. the Kattegat, *reduced* nitrogen emitted from a Danish source close to the coast may even have a larger chance of being deposited to the sea than oxidized nitrogen, because the latter may have a sufficiently long lifetime to get transported to Sweden. Of course, in order to judge a country's importance for nitrogen deposition to the Baltic Sea, the information on transfer coefficients is not sufficient but has to be considered together with the country's total emission.

	DK	**EE**	**FI**	**DE**	**LV**	**LT**	**PL**	**RU**	**SE**	**BAS**	**NOS**	**FR**	**GB**
Ox-N	11 %	10 %	8 %	5 %	9 %	9 %	7 %	0.8 %	11 %	18 %	5 %	1.6 %	2.9 %
Re-N	19 %	15 %	10 %	5 %	10 %	8 %	6 %	0.3 %	17 %	n.a.	n.a.	0.8 %	1.4 %
Tot-N	17 %	13 %	9 %	5 %	10 %	8 %	6 %	0.6 %	15 %	18 %	5 %	1.1 %	2.2 %

Table 5. Transfer coefficients for oxidized, reduced and total nitrogen from different countries. The table answers the question as to how large a percentage of each country's domestic emissions is deposited to the Baltic Sea via the atmosphere. Numbers are given for oxidised, reduced and total airborne nitrogen separately. Example: 10% of Estonia's annual emission of oxidised nitrogen (NOx) is deposited to the Baltic Sea. All calculations are *normalized* and based on emissions of 2021.

3. Results

The calculated contributions from the different countries and emission sectors to nitrogen deposition in the Baltic Sea and its sub-basins in 2021 are presented in the following sections - separately for oxidized, reduced and total nitrogen.

3.1 Oxidized nitrogen deposition

Table 6 lists contributions to oxidized nitrogen deposition in the entire Baltic Sea by country/region and by sector.

The single most important contribution comes from Transport in BAS, i.e. NOx emissions from international shipping in the Baltic Sea. Its contribution amounts to about 18 ktonnes(N) of oxidized nitrogen deposition in the year 2021. However, when summing up all emission sectors, emissions from BAS make the largest contribution (17.9%), followed by Germany (15.2%) and the 'RoEMEP' group of countries/regions (13%). 'EUnonHel' group of countries comes in forth place, down from the first place which it had in the previous study for 2017. This is mainly due to the fact that the Unitited Kingdom now belongs to 'RoEMEP' and not to 'EUnonHel' anymore.

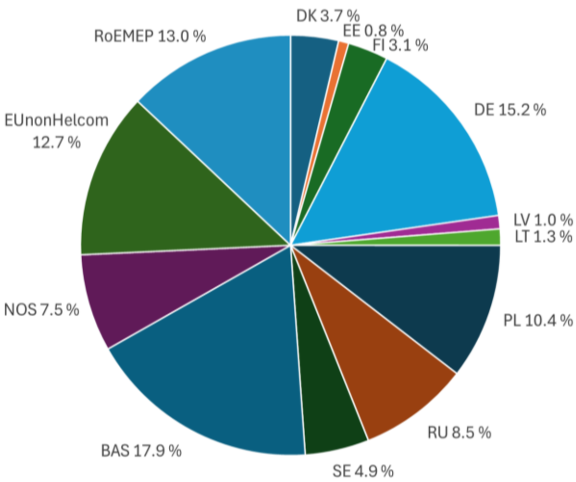
The Transport sector makes by far the largest contribution to oxidized nitrogen deposition in the Baltic Sea (62.1%).

The percentage contributions by countries/regions listed in the second-to-last column of Table 6 and the percentage contributions by sector (last row of Table 6) are visualized as pie charts in Figure 6.

The percentage contribution made by each sector to a county's/region's total contribution is shown in Figure 7. The Transport sector (orange bars) stands for the largest share in all countries/regions. In 5 of the 9 HELCOM countries it stands for more than half of their total contribution to oxidized nitrogen deposition in the Baltic Sea.

	AGR	TRA	POW	OSC	OTH	contribution by country to total	*Results for 2017 (Gauss et al., 2020)*
BAS	0	17998	0	0	0	**17.9 %**	*EUnonHel 21.9%*
DE	1749	6203	3627	1257	2409	**15.2 %**	*DE 17.0%*
RoEMEP	965	6985	1494	769	2840	**13.0 %**	*BAS 14.8%*
EUnonHel	1930	6402	1195	1279	2009	**12.7 %**	*PL 11,6%*
PL	1135	4166	2367	1530	1307	**10.4 %**	*NOS 8.8%*
RU	309	5394	1433	373	1041	**8.5 %**	*RoEMEP 5.9%*
NOS	0	7537	0	0	0	**7.5 %**	*DK 4.8%*
SE	385	2778	569	164	1064	**4.9 %**	*SE 4.6%*
DK	389	2221	486	250	355	**3.7 %**	*RU 4.5%*
FI	266	1170	516	369	799	**3.1 %**	*FI 3.2%*
LT	163	702	161	75	162	**1.3 %**	*LT 1.2%*
LV	103	545	106	87	192	**1.0 %**	*LV 1.0%*
EE	73	346	160	178	30	**0.8 %**	*EE 0.8%*
contribution by sector to total	**7.4 %**	**62.1 %**	**12.0 %**	**6.3 %**	**12.1 %**	Total deposition: 100.6 kt(N)/year	*Total dep: 122.6 kt(N)/year*

Table 6. Contributions from different countries/regions and sectors to oxidized nitrogen deposition in the entire Baltic Sea. Unit: tonnes(N)/year. Source countries/regions are sorted vertically by their percentage contribution to oxidized nitrogen deposition ("contribution by country to total", from largest to smallest). For comparison, the results from the last report (for 2017) are given in grey font in the last column.



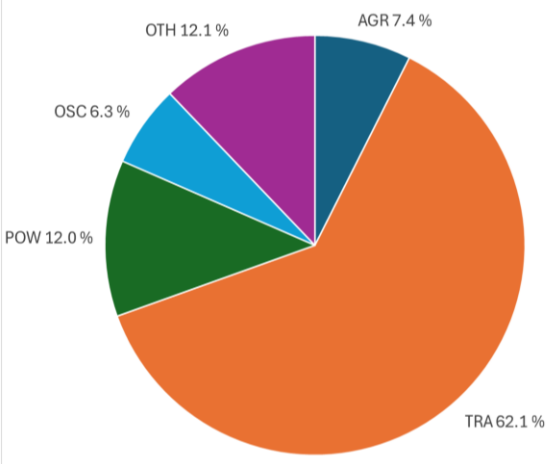


Figure 6. Contributions from different countries/regions (left pie) and from different sectors (right pie) to deposition of oxidized nitrogen in the Baltic Sea in 2021. The pie charts are based on the percentages given in bold type in Table 6.

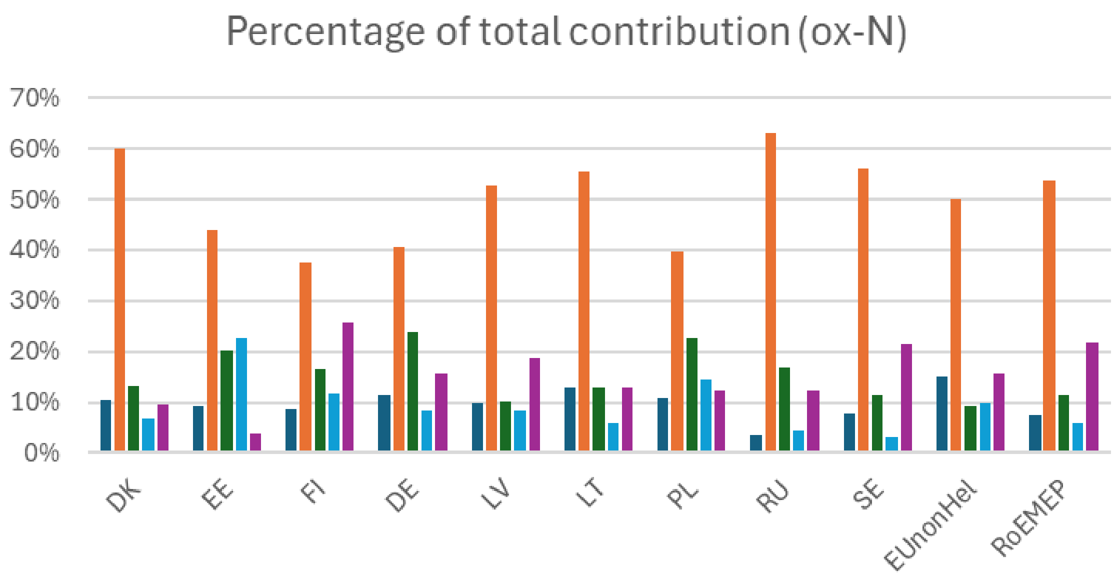


Figure 7. Percentage contribution made by each sector to the country's/region's total contribution to oxidized nitrogen deposition in the Baltic Sea in 2021. For each country/region, the 5 bars sum up to 100%, corresponding to the country's/region's total contribution.

Figures 8 and 9 show the horizontal distribution of oxidized nitrogen deposition contributed by the Transport sector in different countries/regions in 2021. The Transport sector is chosen here as an example as it has the largest impact on oxidized nitrogen deposition among the five sectors considered in this study. In general, the source country/region affects itself the most (in terms of deposition per unit area), but long-range transport does occur, with somewhat longer transport distances to the east than to the west. Counterintuitively, the effect of NOx emissions from NOS and BAS peaks over land (coastal regions). This is because nitrogen is more easily deposited over land surfaces than on water.

Table 7 contains the same information as Table 6, but sorts all the contributions from sources considered in this study from largest to smallest. As mentioned above, Transport from BAS tops this list, but there are many other Transport contributions among the top 10. The top 10 contributions make up almost 64% of the total, while the top 25 contributions constitute about 90% of the total.

Finally, Table 8 lists the top 25 contributions among the considered sources for each of the 9 sub-basins of the Baltic Sea. Transport emissions are strongly represented in this table, and of course the geographic location of countries/regions with respect to the sub-basin in question plays a role. For example, German emission sectors contribute less to the Bothnian Bay than to the Western Baltic (due to the larger distance), and Sweden plays a larger role for the sub-basins located east of it than west of it, due to the predominantly (on annual average) westerly wind direction.

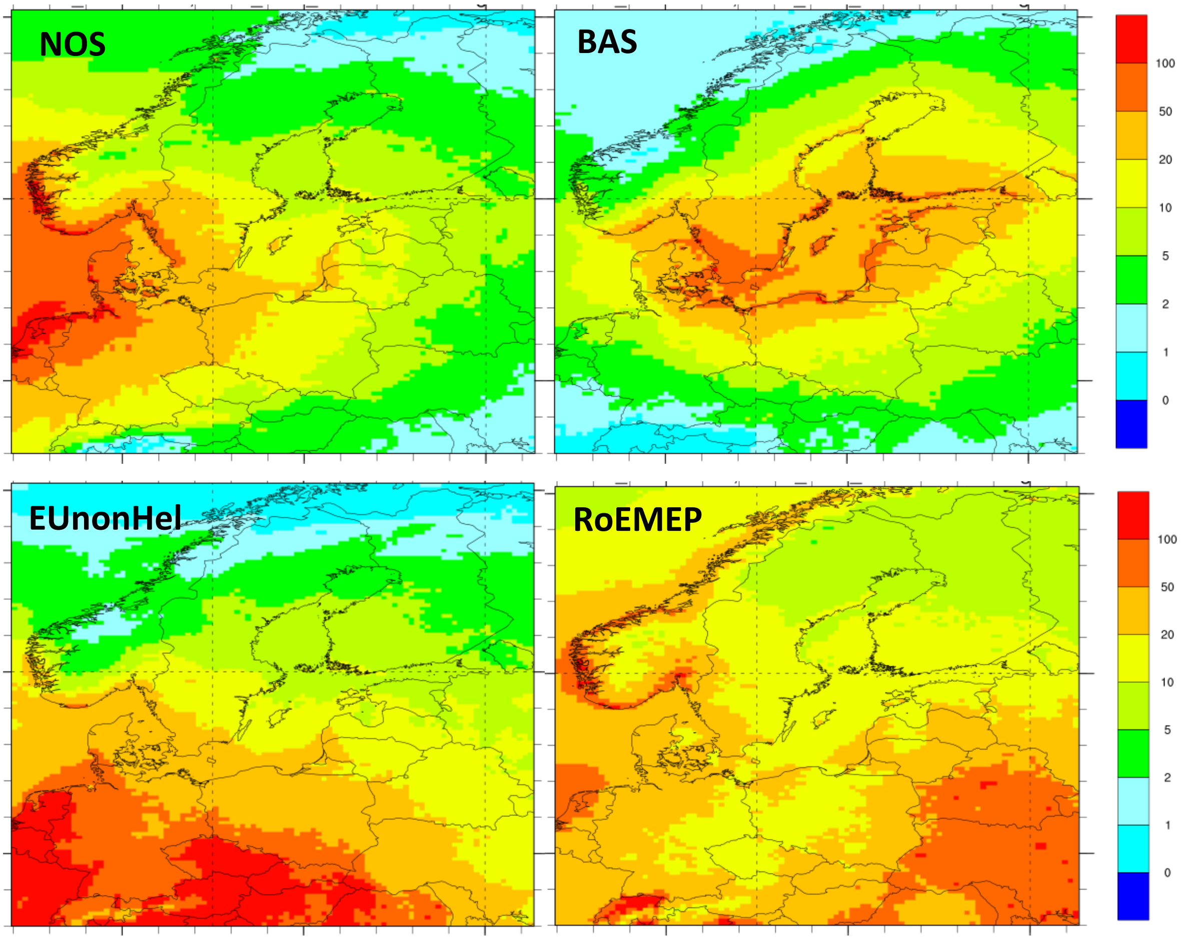


Figure 8. Distribution of contributions to oxidized nitrogen deposition due to Transport emissions from NOS, BAS, EUnonHel and RoEMEP in 2021. Unit: kg(N)/km^2/year.

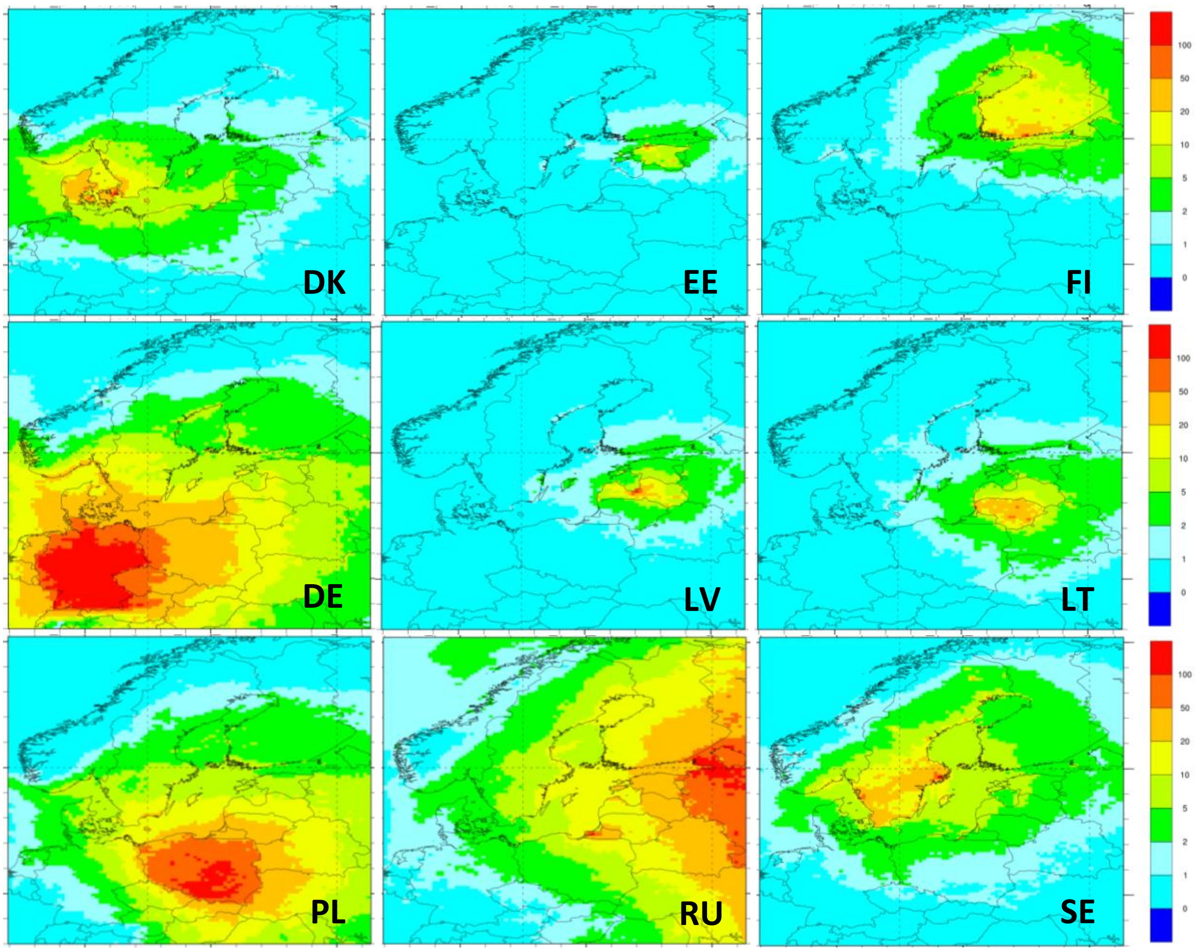


Figure 9. Distribution of contributions to oxidized nitrogen deposition due to Transport emissions from HELCOM Parties in 2021. Unit: kg(N)/km^2/year.

			Ox-N	Perc.				Ox-N	Perc.
1	BAS	TRA	17998	17.9 %	**31**	LT	TRA	702	0.7 %
2	NOS	TRA	7537	7.5 %	**32**	SE	POW	569	0.6 %
3	RoEMEP	TRA	6985	6.9 %	**33**	LV	TRA	545	0.5 %
4	EUnonHel	TRA	6402	6.4 %	**34**	FI	POW	516	0.5 %
5	DE	TRA	6203	6.2 %	**35**	DK	POW	486	0.5 %
6	RU	TRA	5394	5.4 %	**36**	DK	AGR	389	0.4 %
7	PL	TRA	4166	4.1 %	**37**	SE	AGR	385	0.4 %
8	DE	POW	3627	3.6 %	**38**	RU	OSC	373	0.4 %
9	RoEMEP	OTH	2840	2.8 %	**39**	FI	OSC	369	0.4 %
10	SE	TRA	2778	2.8 %	**40**	DK	OTH	355	0.4 %
11	DE	OTH	2409	2.4 %	**41**	EE	TRA	346	0.3 %
12	PL	POW	2367	2.4 %	**42**	RU	AGR	309	0.3 %
13	DK	TRA	2221	2.2 %	**43**	FI	AGR	266	0.3 %
14	EUnonHel	OTH	2009	2.0 %	**44**	DK	OSC	250	0.2 %
15	EUnonHel	AGR	1930	1.9 %	**45**	LV	OTH	192	0.2 %
16	DE	AGR	1749	1.7 %	**46**	EE	OSC	178	0.2 %
17	PL	OSC	1530	1.5 %	**47**	SE	OSC	164	0.2 %
18	RoEMEP	POW	1494	1.5 %	**48**	LT	AGR	163	0.2 %
19	RU	POW	1433	1.4 %	**49**	LT	OTH	162	0.2 %
20	PL	OTH	1307	1.3 %	**50**	LT	POW	161	0.2 %
21	EUnonHel	OSC	1279	1.3 %	**51**	EE	POW	160	0.2 %
22	DE	OSC	1257	1.2 %	**52**	LV	POW	106	0.1 %
23	EUnonHel	POW	1195	1.2 %	**53**	LV	AGR	103	0.1 %
24	FI	TRA	1170	1.2 %	**54**	LV	OSC	87	0.1 %
25	PL	AGR	1135	1.1 %	**55**	LT	OSC	75	0.1 %
26	SE	OTH	1064	1.1 %	**56**	EE	AGR	73	0.1 %
27	RU	OTH	1041	1.0 %	**57**	EE	OTH	30	0.0 %
28	RoEMEP	AGR	965	1.0 %					
29	FI	OTH	799	0.8 %					
30	RoEMEP	OSC	769	0.8 %					

Table 7. List of all sources considered in this study, sorted (from largest to smallest) by their contribution to total airborne deposition of oxidized nitrogen in the Baltic Sea in 2021. ‘Ox-N’: contribution to oxidized nitrogen deposition in the Baltic Sea in 2021 given in tonnes(N), ‘Perc.’: percentage of total. Example: The Transport sector in Finland contributed 1170 tonnes(N) to oxidized nitrogen deposition in the Baltic Sea, which was the 24th largest single contribution among the sources considered in this study and corresponds to 1.2% of the total deposition of airborne oxidized nitrogen in the Baltic Sea in 2021. The sum of all percentages listed in this table equals 100% and corresponds to the calculated total annual value of 100.6 ktonnes(N). BAS and NOS contributions from other sectors than transport are not listed here as they are exactly zero.

BOB			BOS			GUF		
BAS	TRA	519	BAS	TRA	1491	BAS	TRA	1398
RU	TRA	468	RoEMEP	TRA	741	RU	TRA	1244
RoEMEP	TRA	313	RU	TRA	617	RoEMEP	TRA	459
FI	TRA	246	EUnonHel	TRA	485	RU	POW	274
FI	OTH	208	NOS	TRA	458	NOS	TRA	255
SE	TRA	171	SE	TRA	457	EUnonHel	TRA	243
EUnonHel	TRA	157	DE	TRA	307	RU	OTH	226
NOS	TRA	154	PL	TRA	280	FI	TRA	225
RU	POW	128	FI	TRA	268	RoEMEP	OTH	180
SE	OTH	119	RoEMEP	OTH	260	DE	TRA	150
RoEMEP	OTH	113	SE	OTH	251	FI	OTH	145
DE	TRA	109	DE	POW	197	SE	TRA	137
RU	OTH	97	PL	POW	191	PL	TRA	133
PL	TRA	88	EUnonHel	AGR	183	EE	TRA	128
FI	POW	84	RU	POW	183	RoEMEP	POW	121
FI	OSC	84	FI	OTH	173	DE	POW	95
DE	POW	70	PL	AGR	154	RoEMEP	AGR	93
EUnonHel	AGR	68	EUnonHel	OTH	146	FI	POW	91
RoEMEP	POW	59	RoEMEP	POW	146	RU	OSC	90
RoEMEP	AGR	59	RU	OTH	122	EUnonHel	AGR	84
FI	AGR	59	RoEMEP	AGR	117	PL	POW	83
PL	POW	58	DE	OTH	112	EUnonHel	OTH	74
PL	AGR	51	FI	POW	108	DE	AGR	69
EUnonHel	OTH	43	SE	POW	103	LV	TRA	68
DE	AGR	42	PL	OSC	102	FI	OSC	64
88%			85%			86%		

Table 8. Top 25 contributions to oxidized nitrogen deposition in 2021, listed for each of the nine sub-basins of the Baltic Sea separately. Unit: tonnes(N)/year. The numbers in the bottom row give the percentage of these 25 contributions to the total deposition of oxidized nitrogen in the respective sub-basin. The table continues on the next two pages.

GUR			BAP			SOU		
BAS	TRA	716	BAS	TRA	10716	BAS	TRA	180
RU	TRA	355	NOS	TRA	4057	NOS	TRA	99
RoEMEP	TRA	304	DE	TRA	3926	DE	TRA	76
NOS	TRA	206	RoEMEP	TRA	3747	EUnonHel	TRA	74
EUnonHel	TRA	193	EUnonHel	TRA	3694	DK	TRA	67
DE	TRA	174	PL	TRA	3045	RoEMEP	TRA	61
PL	TRA	172	RU	TRA	2367	DE	POW	43
RoEMEP	OTH	124	DE	POW	2299	DE	OTH	32
LV	TRA	118	PL	POW	1664	SE	TRA	31
DE	POW	116	RoEMEP	OTH	1576	PL	TRA	25
RU	POW	103	DE	OTH	1523	RoEMEP	OTH	25
SE	TRA	95	SE	TRA	1480	EUnonHel	OTH	24
PL	POW	86	EUnonHel	OTH	1178	DE	AGR	21
LT	TRA	81	DK	TRA	1129	EUnonHel	AGR	19
DE	AGR	78	PL	OSC	1127	DE	OSC	16
PL	AGR	76	EUnonHel	AGR	1060	EUnonHel	OSC	15
RoEMEP	POW	75	DE	AGR	1018	PL	POW	14
RU	OTH	69	PL	OTH	956	EUnonHel	POW	12
EUnonHel	AGR	68	RoEMEP	POW	833	RoEMEP	POW	12
DE	OTH	65	DE	OSC	785	PL	OSC	9
PL	OSC	60	EUnonHel	OSC	743	PL	OTH	8
EUnonHel	OTH	58	EUnonHel	POW	726	RoEMEP	OSC	8
PL	OTH	52	RU	POW	651	RU	TRA	7
DK	TRA	50	PL	AGR	630	PL	AGR	7
RoEMEP	AGR	50	RoEMEP	AGR	495	DK	OSC	7
84%			**91%**			**96%**		

Table 8. cont’d.

KAT			ARC			WEB		
BAS	TRA	1247	BAS	TRA	738	NOS	TRA	915
NOS	TRA	1130	RoEMEP	TRA	213	BAS	TRA	872
EUnonHel	TRA	647	RU	TRA	195	DE	TRA	830
RoEMEP	TRA	608	NOS	TRA	149	EUnonHel	TRA	772
DE	TRA	547	EUnonHel	TRA	139	RoEMEP	TRA	544
DK	TRA	431	SE	TRA	126	DE	POW	438
DE	POW	309	FI	TRA	92	DK	TRA	347
RoEMEP	OTH	256	DE	TRA	89	DE	OTH	327
DE	OTH	232	PL	TRA	88	EUnonHel	OTH	245
SE	TRA	213	RoEMEP	OTH	81	RoEMEP	OTH	227
DE	AGR	211	PL	POW	58	EUnonHel	AGR	199
EUnonHel	OTH	201	DE	POW	58	DE	AGR	176
EUnonHel	AGR	198	RU	POW	55	DE	OSC	172
PL	TRA	187	FI	OTH	53	PL	TRA	149
EUnonHel	OSC	127	RoEMEP	POW	48	EUnonHel	OSC	149
PL	POW	118	EUnonHel	AGR	47	EUnonHel	POW	119
DE	OSC	116	EUnonHel	OTH	42	RoEMEP	POW	96
EUnonHel	POW	103	SE	OTH	41	PL	POW	94
RoEMEP	POW	101	RU	OTH	39	SE	TRA	73
RU	TRA	85	RoEMEP	AGR	38	RoEMEP	OSC	73
DK	OTH	75	PL	AGR	37	PL	OSC	56
RoEMEP	OSC	75	DE	OTH	34	RU	TRA	55
PL	AGR	74	DE	AGR	33	PL	OTH	50
DK	POW	71	DK	TRA	32	RoEMEP	AGR	44
PL	OSC	67	PL	OSC	32	PL	AGR	43
94%			86%			96%		

Table 8. cont'd.

3.2 Reduced nitrogen deposition

Table 9 lists contributions to reduced nitrogen deposition in the entire Baltic Sea by country/region and by sector. The single largest contribution comes from Agriculture in DE, i.e. ammonia emissions from the agricultural sector in Germany. Its contribution amounts to about 20 ktonnes(N) of reduced nitrogen deposition in the year 2021. Also when summing up all sectors, Germany makes the largest contribution (about 23% of the total deposition of reduced nitrogen in the Baltic Sea in 2017), followed by Poland, EUnonHel, and Denmark.

The percentage contributions by countries/regions listed in the second-to-last column of Table 9 and the percentage contributions by sector (last row of Table 9) are visualized as pie charts in Figure 10.

The percentage contribution made by each sector to a county's/region's total contribution is shown in Figure 11. As the Agriculture sector (blue bars) stands for by far the largest emission of reduced nitrogen in all countries/regions, it is not surprising that it also makes by far the largest contribution among the 5 selected sectors for every country/region (92.4%).

As seen in Table 9, there are some small negative contributions as well. Amounting typically to a few tens of tonnes(N)/year, these are negligible compared to the total deposition of reduced nitrogen to the Baltic Sea (90 505 tonnes/year). They are due to chemical interactions between reduced and oxidized nitrogen. E.g. the Power sector emits almost exclusively oxidized nitrogen, but this oxidized nitrogen can lead to more particle formation and thus to longer transport distances of reduced nitrogen (particles are less easily deposited than gases). Therefore, small reductions can occur due to emissions from Power in some countries, as seen in Table 9 and Figure 11. Similar statements can be made for the OSC sector. The degree to which this effect is reduced or overwhelmed by co-emitted reduced nitrogen depends on the country, its energy mix, the chemical regime and the geographic distance from the Baltic Sea. However, common to all cases is that this effect is very small.

	AGR	TRA	POW	OSC	OTH	contribution by country to total	*Results for 2017 (Gauss et al., 2020)*
DE	19873	233	-13	40	850	**23.2 %**	*DE 30.7 %*
PL	13499	123	-112	-118	274	**15.1 %**	*EUnonHel 19.4 %*
EUnonHel	11694	356	71	345	759	**14.6 %**	*DK 13.9 %*
DK	11785	18	-39	239	180	**13.5 %**	*PL 13.7 %*
RU	7031	696	8	1	576	**9.2 %**	*SE 8.2 %*
RoEMEP	7240	216	61	104	650	**9.1 %**	*RoEMEP 4.7 %*
SE	6695	143	42	13	556	**8.2 %**	*FI 3.0 %*
FI	2087	58	-18	94	129	**2.6 %**	*RU 2.5 %*
LT	1939	7	26	8	40	**2.2 %**	*LT 1.7 %*
LV	940	4	-4	130	79	**1.3 %**	*LV 1.2 %*
EE	855	15	-21	3	44	**1.0 %**	*EE 1.0 %*
contribution by sector to total	**92.4 %**	**2.1 %**	**0.0 %**	**0.9 %**	**4.6 %**	Total deposition: 90.5 kt(N)/year	*Total deposition: 105.3 kt(N)/year*

Table 9. Contributions from different countries/regions and sectors to reduced nitrogen deposition in the entire Baltic Sea. Unit: tonnes(N)/year. Source countries/regions are sorted vertically by their percentage contribution to reduced nitrogen deposition ("contribution by country to total", from largest to smallest). For comparison, the results from the last report (for 2017) are given in grey font in the last column.

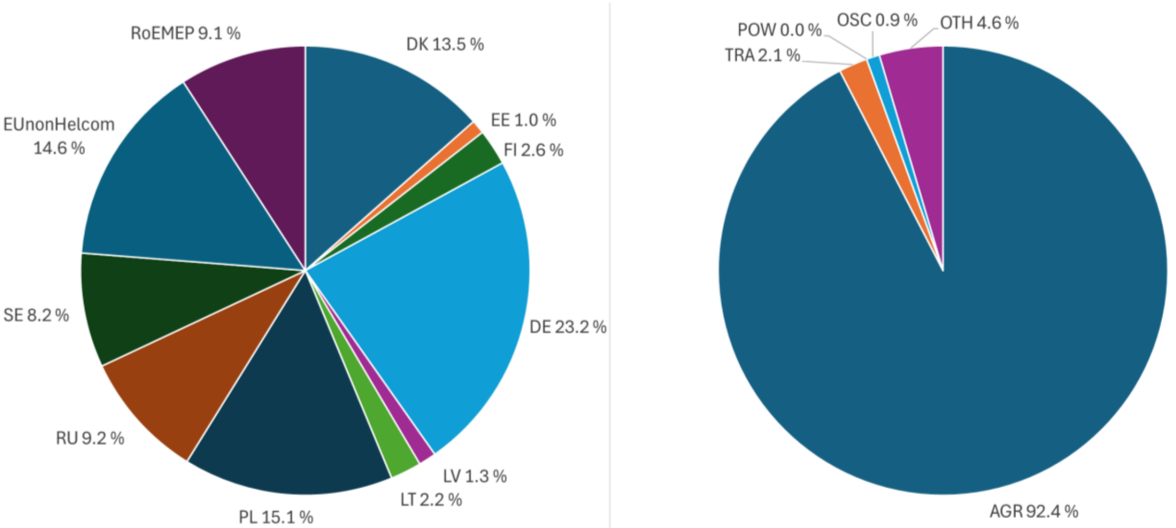


Figure 10. Contributions from different countries/regions (left pie) and from sectors (right pie) to deposition of reduced nitrogen in the Baltic Sea in 2021. The pie charts are based on the percentages given in bold type in Table 9.

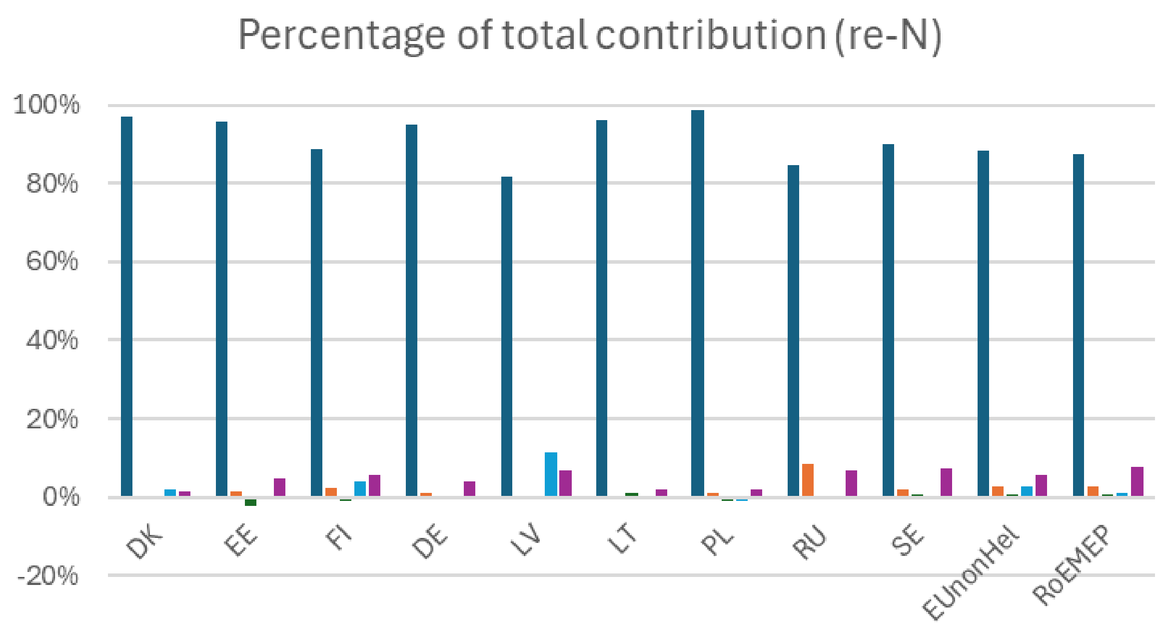


Figure 11. Percentage contribution made by each sector to the country's/region's total contribution to reduced nitrogen deposition in the Baltic Sea in 2021. For each country/region, the 5 bars sum up to approximately 100%, corresponding to the country's/region's total contribution.

Figures 12 and 13 show the horizontal distribution of reduced nitrogen deposition contributed by the Agriculture sector in different countries/regions in 2021. The Agriculture sector is chosen here as an example as it has the largest impact on reduced nitrogen deposition among the five sectors considered in this study. In general, the source country/region affects itself the most (in terms of deposition per unit area), but long-range transport does occur, with somewhat longer transport distances to the east than to the west. Nevertheless, the effects are more confined to the source countries/regions than in the case of oxidized nitrogen (compare with Figures 8 and 9), which is related to the shorter lifetime of reduced nitrogen in the atmosphere. The effect from NOS and BAS are zero, as no ammonia is emitted from international shipping.

Table 10 contains the same information as Table 9, but sorts all the contributions from sources considered in this study from largest to smallest. As mentioned above, Agriculture from DE tops this list, but there are many other Agriculture contributions among the top 10. The top 10 contributions make up 91.5% of the total, while the top 25 contributions account for about 99% of the total.

Finally, Table 11 lists the top 25 contributions among the considered sources for each of the 9 sub-basins of the Baltic Sea. Agriculture emissions are strongly represented in this table, and of course the geographic location of countries/regions with respect to the sub-basin in question plays a role also in this case.

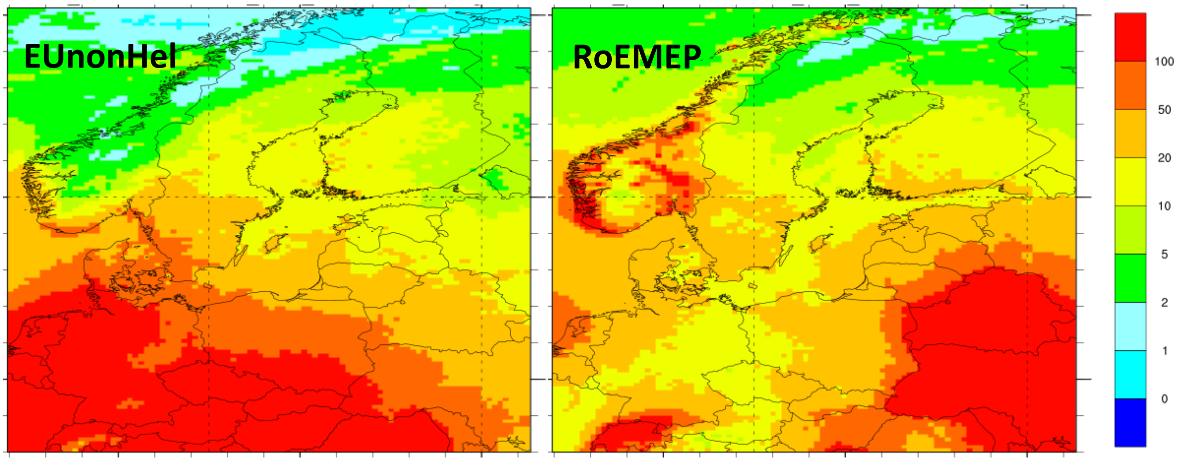


Figure 12. Contribution to reduced nitrogen deposition from Agriculture emissions from the EUnonHel group of countries (left) and the 'RoEMEP' group of countries/regions in 2021. Unit: kg(N)/km^2/year.

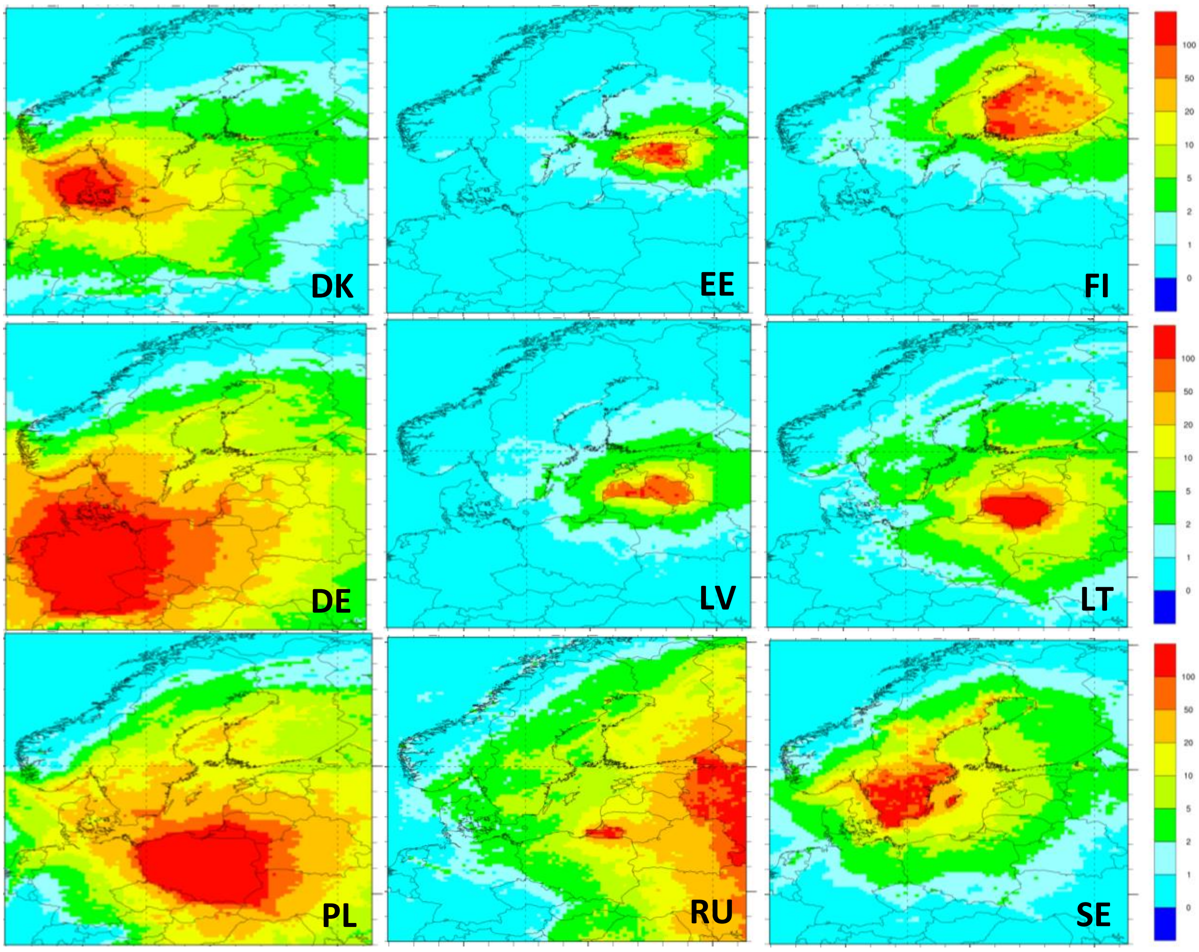


Figure 13. Contribution to reduced nitrogen deposition from Agriculture emissions from HELCOM parties in 2021. Unit: kg(N)/km^2/year.

			Re-N	Perc.				Re-N	Perc.
1	DE	AGR	19873	22.0 %	31	LV	OTH	79	0.1 %
2	PL	AGR	13499	14.9 %	32	EUnonHel	POW	71	0.1 %
3	DK	AGR	11785	13.0 %	33	RoEMEP	POW	61	0.1 %
4	EUnonHel	AGR	11694	12.9 %	34	FI	TRA	58	0.1 %
5	RoEMEP	AGR	7240	8.0 %	35	EE	OTH	44	0.0 %
6	RU	AGR	7031	7.8 %	36	SE	POW	42	0.0 %
7	SE	AGR	6695	7.4 %	37	LT	OTH	40	0.0 %
8	FI	AGR	2087	2.3 %	38	DE	OSC	40	0.0 %
9	LT	AGR	1939	2.1 %	39	LT	POW	26	0.0 %
10	LV	AGR	940	1.0 %	40	DK	TRA	18	0.0 %
11	EE	AGR	855	0.9 %	41	EE	TRA	15	0.0 %
12	DE	OTH	850	0.9 %	42	SE	OSC	13	0.0 %
13	EUnonHel	OTH	759	0.8 %	43	LT	OSC	8	0.0 %
14	RU	TRA	696	0.8 %	44	RU	POW	8	0.0 %
15	RoEMEP	OTH	650	0.7 %	45	LT	TRA	7	0.0 %
16	RU	OTH	576	0.6 %	46	LV	TRA	4	0.0 %
17	SE	OTH	556	0.6 %	47	EE	OSC	3	0.0 %
18	EUnonHel	TRA	356	0.4 %	48	RU	OSC	1	0.0 %
19	EUnonHel	OSC	345	0.4 %	49	BAS	TRA	0	0.0 %
20	PL	OTH	274	0.3 %	50	NOS	TRA	0	0.0 %
21	DK	OSC	239	0.3 %	51	LV	POW	-4	0.0 %
22	DE	TRA	233	0.3 %	52	DE	POW	-13	0.0 %
23	RoEMEP	TRA	216	0.2 %	53	FI	POW	-18	0.0 %
24	DK	OTH	180	0.2 %	54	EE	POW	-21	0.0 %
25	SE	TRA	143	0.2 %	55	DK	POW	-39	0.0 %
26	LV	OSC	130	0.1 %					
27	FI	OTH	129	0.1 %					
28	PL	TRA	123	0.1 %					
29	RoEMEP	OSC	104	0.1 %					
30	FI	OSC	94	0.1 %					

Table 10. List of all sources considered in this study, sorted (from largest to smallest) by their contribution to total airborne deposition of reduced nitrogen in the Baltic Sea in 2021. 'Re-N': contribution to reduced nitrogen deposition in the Baltic Sea in 2021 given in tonnes(N), 'Perc.': percentage of total positive. Example: The Agricultural sector in Latvia contributed 940 tonnes(N) to reduced nitrogen deposition in the Baltic Sea, which was the 10th largest single contribution among the sources considered in this study and corresponds to 1.0% of the total deposition of airborne reduced nitrogen in the Baltic Sea in 2021. The sum of all percentages listed in this table equals 100% and corresponds to the calculated total annual value of 90.5 ktonnes(N).

BOB			BOS			GUF		
FI	AGR	615	PL	AGR	1107	RU	AGR	1641
RU	AGR	414	EUnonHel	AGR	967	RoEMEP	AGR	457
PL	AGR	316	RoEMEP	AGR	729	EE	AGR	308
EUnonHel	AGR	299	RU	AGR	726	FI	AGR	304
RoEMEP	AGR	273	SE	AGR	691	EUnonHel	AGR	296
SE	AGR	212	FI	AGR	587	PL	AGR	242
DE	AGR	204	DE	AGR	580	DE	AGR	233
RU	TRA	57	DK	AGR	178	RU	TRA	211
DK	AGR	57	LT	AGR	134	RU	OTH	200
SE	OTH	45	SE	OTH	134	SE	AGR	141
RU	OTH	44	RU	TRA	74	LT	AGR	114
LT	AGR	37	EUnonHel	OTH	69	DK	AGR	103
RoEMEP	OTH	28	RoEMEP	OTH	67	LV	AGR	73
EUnonHel	OTH	26	RU	OTH	66	RoEMEP	OTH	36
FI	OSC	25	EE	AGR	60	EUnonHel	OTH	30
DE	OTH	22	LV	AGR	58	DE	OTH	24
EE	AGR	21	EUnonHel	TRA	56	EE	OTH	22
EUnonHel	TRA	21	DE	OTH	47	EUnonHel	TRA	22
FI	OTH	21	EUnonHel	OSC	41	FI	OSC	18
RoEMEP	POW	19	RoEMEP	POW	40	FI	TRA	15
LV	AGR	16	FI	OTH	38	EUnonHel	OSC	15
RoEMEP	TRA	16	RoEMEP	TRA	38	RoEMEP	TRA	15
DE	TRA	15	DE	TRA	31	SE	OTH	15
EUnonHel	OSC	15	PL	OTH	27	DE	TRA	14
PL	POW	13	SE	TRA	27	FI	OTH	12
96%			97%			98%		

Table 11. Top 25 contributions to reduced nitrogen deposition in 2021, listed for each of the nine sub-basins of the Baltic Sea separately. Unit: tonnes(N)/year. The numbers in the bottom row give the percentage of these 25 contributions to the total deposition of reduced nitrogen in the respective sub-basin. The table continues on the next two pages.

GUR			BAP			SOU		
RU	AGR	448	DE	AGR	10873	DK	AGR	294
RoEMEP	AGR	436	PL	AGR	10039	DE	AGR	250
PL	AGR	396	EUnonHel	AGR	6538	EUnonHel	AGR	140
DE	AGR	318	SE	AGR	4417	SE	AGR	99
EUnonHel	AGR	296	DK	AGR	4298	PL	AGR	74
LV	AGR	255	RoEMEP	AGR	4099	RoEMEP	AGR	51
LT	AGR	245	RU	AGR	3392	DK	OSC	15
EE	AGR	165	LT	AGR	1296	RU	AGR	14
SE	AGR	156	DE	OTH	507	DE	OTH	11
DK	AGR	113	LV	AGR	493	DK	TRA	10
FI	AGR	53	EUnonHel	OTH	423	DK	OTH	9
LV	OSC	46	RoEMEP	OTH	380	EUnonHel	OTH	8
RU	TRA	40	FI	AGR	282	SE	OTH	5
DE	OTH	30	RU	TRA	269	RoEMEP	OTH	5
RoEMEP	OTH	26	SE	OTH	265	SE	TRA	4
EUnonHel	OTH	25	EE	AGR	262	LT	AGR	3
LV	OTH	23	RU	OTH	210	EUnonHel	OSC	3
DE	TRA	20	EUnonHel	OSC	189	EUnonHel	TRA	2
EUnonHel	TRA	18	EUnonHel	TRA	187	PL	OTH	2
RU	OTH	16	PL	OTH	179	PL	TRA	1
PL	OTH	14	DE	TRA	147	FI	AGR	1
EUnonHel	OSC	13	RoEMEP	TRA	129	LV	AGR	1
SE	OTH	12	DK	OSC	86	EE	AGR	1
RoEMEP	TRA	12	SE	TRA	69	SE	POW	1
DE	POW	11	DK	OTH	63	RoEMEP	OSC	0
99%			100%			100%		

Table 11. Cont’d.

KAT			ARC			WEB		
DK	AGR	3440	EUnonHel	AGR	270	DE	AGR	5504
DE	AGR	1776	PL	AGR	246	DK	AGR	3237
EUnonHel	AGR	1303	RoEMEP	AGR	239	EUnonHel	AGR	1603
SE	AGR	669	FI	AGR	225	PL	AGR	491
PL	AGR	602	RU	AGR	200	RoEMEP	AGR	432
RoEMEP	AGR	538	SE	AGR	177	SE	AGR	142
RU	AGR	140	DE	AGR	157	DE	OTH	102
DE	OTH	83	DK	AGR	66	RU	AGR	89
EUnonHel	OTH	78	LT	AGR	65	EUnonHel	OTH	77
DK	OSC	66	FI	OTH	32	DK	OSC	60
DK	OTH	57	EE	AGR	29	RoEMEP	OTH	38
SE	OTH	49	LV	AGR	28	DK	OTH	33
RoEMEP	OTH	47	RoEMEP	OTH	24	EUnonHel	OSC	22
EUnonHel	TRA	39	RU	TRA	24	LT	AGR	16
EUnonHel	OSC	32	EUnonHel	OTH	19	SE	OTH	8
LT	AGR	29	SE	OTH	19	FI	AGR	6
SE	TRA	18	RU	OTH	18	LV	AGR	6
DE	TRA	15	DE	OTH	16	EE	AGR	4
PL	OTH	15	EUnonHel	TRA	14	DK	TRA	3
FI	AGR	13	RoEMEP	TRA	11	RU	OTH	3
PL	TRA	9	EUnonHel	OSC	10	PL	OTH	3
LV	AGR	9	RoEMEP	POW	10	RU	TRA	1
EUnonHel	POW	7	DE	TRA	9	LV	OSC	1
EE	AGR	7	FI	OSC	9	PL	TRA	1
RU	TRA	6	PL	OTH	8	LV	OTH	0
100%			97%			100%		

Table 11. Cont'd.

3.3 Total nitrogen deposition

Total nitrogen is calculated as the sum of oxidized and reduced nitrogen.

Table 12 lists contributions to total nitrogen deposition in the entire Baltic Sea by country/region and by sector. The single largest contribution comes from Agriculture in DE, amounting to about 22 ktonnes(N) of total nitrogen deposition in the year 2021. Also when summing up all sectors, Germany makes the largest contribution (corresponding to about 19% of the total deposition of total nitrogen in the Baltic Sea in 2021), followed by EUnonHel (13.6%), Poland (12.7%), and 'RoEMEP' (11.2%).

The Agriculture sector makes by the largest contribution to total nitrogen deposition in the Baltic Sea (47.7%), followed by the Transport sector (33.7%). Together they thus stand for more than four fifths of the nitrogen input from the atmosphere to the Baltic Sea.

The percentage contributions by countries/regions listed in the second-to-last column of Table 12 and the percentage contributions by sector (last row of Table 12) are visualized as pie charts in Figure 14.

The percentage contribution made by each sector to a county's/region's total contribution is shown in Figure 15. Agriculture dominates for all countries, followed by the Transport sector.

Table 12 also lists the results for total country contributions that were calculated in the previous project for 2017 conditions (Gauss et al., 2020). In this context it is interesting to note that the actual total nitrogen deposition was much smaller in 2021 than in 2017 (191 vs 228 kt(N)). This is due to a combination of changes in emissions and the model version, as well as the effect of meteorology. Figure 16 shows actual and normalized total nitrogen deposition for the last ten years, as calculated in 2023. The actual value for 2017 is 225 kt(N), i.e. 3 kt(N) less than listed in Table 12. This is due to the updates of the EMEP model since Gauss et al. (2020). Further, the normalized depositions decreased by about 28 kt(N) from 2017 to 2021. Normalized depositions, as calculated by EMEP MSC-W, largely follow emission change (as they filter out meteorological variability). Finally, the maximum and minimum values indicate depositions that would occur if meteorological conditions were most favorable/unfavorable to deposition. The fact that the actual and normalized values for 2017 almost coincide indicates that 2017 was rather normal, while for 2021, meteorological conditions lead to lower-than-normal deposition, the difference amounting to about 6 kt(N). Thus, the overall difference between actual values reported for 2017 (Gauss et al.. 2020) and for 2021 in this report are mainly due to emission change (explaining about 76% of it) followed by meteorological conditions (16%), and model updates (8%). However, how much of the change in emissions (e.g. 3677 kt(N) in 2017 from the nine HELCOM countries vs. 3467 kt(N) in 2021) is due to Covid-19 and how much reflects a long-term trend in emissions remains difficult to estimate based on the data available to us.

Table 13 contains the same information as Table 12, but sorts all the contributions from sources considered in this study from largest to smallest. As mentioned above, Agriculture from DE tops this list, but there are many other Agriculture contributions among the top 10. Transport stands out as the second most important contributor to total nitrogen deposition in the Baltic Sea, with BAS Transport emissions actually coming in second place in Table 13. The top 10 contributions in this table make up 61.4% of the total, while the top 25 contributions account for nearly 90% of the total.

Finally, Table 14 contains the top 25 contributions by sub-basin for total nitrogen deposition in 2021. The top 10 spots for each sub-basin are almost exclusively populated by contributions from Transport and Agriculture, but also in this case, the contributions from other sectors are not negligible.

	AGR	TRA	POW	OSC	OTH	contribution by country to total	*Results for 2017 (Gauss et al., 2020)*
DE	21622	6437	3614	1296	3259	**19.0 %**	*DE 23.3 %*
EUnonHel	13624	6758	1266	1625	2768	**13.6 %**	*EUnonHel 20.7 %*
PL	14634	4290	2255	1412	1581	**12.7 %**	*PL 12.5 %*
RoEMEP	8205	7201	1555	873	3490	**11.2 %**	*DK 9.0 %*
BAS	0	17998	0	0	0	**9.4 %**	*BAS 8.0 %*
RU	7340	6091	1441	374	1617	**8.8 %**	*SE 6.2 %*
DK	12174	2239	447	489	534	**8.3 %**	*RoEMEP 5.4 %*
SE	7080	2921	611	177	1620	**6.5 %**	*NOS 4.7 %*
NOS	0	7537	0	0	0	**3.9 %**	*RU 3.5 %*
FI	2353	1228	498	463	928	**2.9 %**	*FI 3.1 %*
LT	2102	709	187	84	203	**1.7 %**	*LT 1.4 %*
LV	1043	549	102	217	271	**1.1 %**	*LV 1.1 %*
EE	928	361	139	181	74	**0.9 %**	*EE 0.9 %*
contribution by sector to total	**47.7 %**	**33.7 %**	**6.3 %**	**3.8 %**	**8.6 %**	Total deposition: 191.1 kt(N)/year	*Total deposition: 227.9 kt(N)/year*

Table 12. Contributions from different countries/regions and sectors to total nitrogen deposition in the entire Baltic Sea. Unit: tonnes(N)/year. Source countries/regions are sorted vertically by their percentage contribution to total nitrogen deposition ("contribution by country to total", from largest to smallest). For comparison, the results from the last report (for 2017) are given in grey font in the last column.

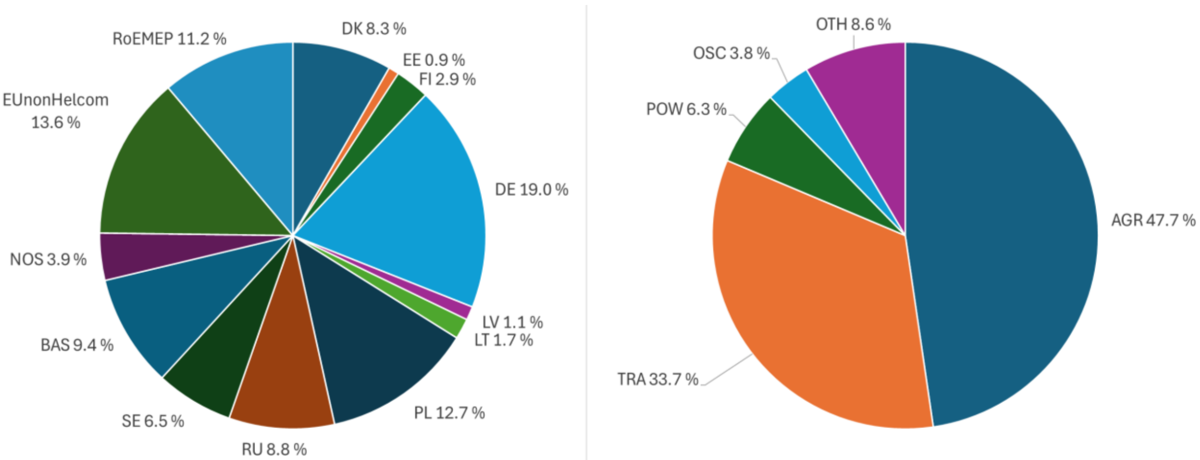


Figure 14. Contributions from different countries/regions (left pie) and sectors (right pie) to the deposition of total nitrogen in the Baltic Sea in 2021. The pie charts are based on the percentages given in bold type in Table 12.

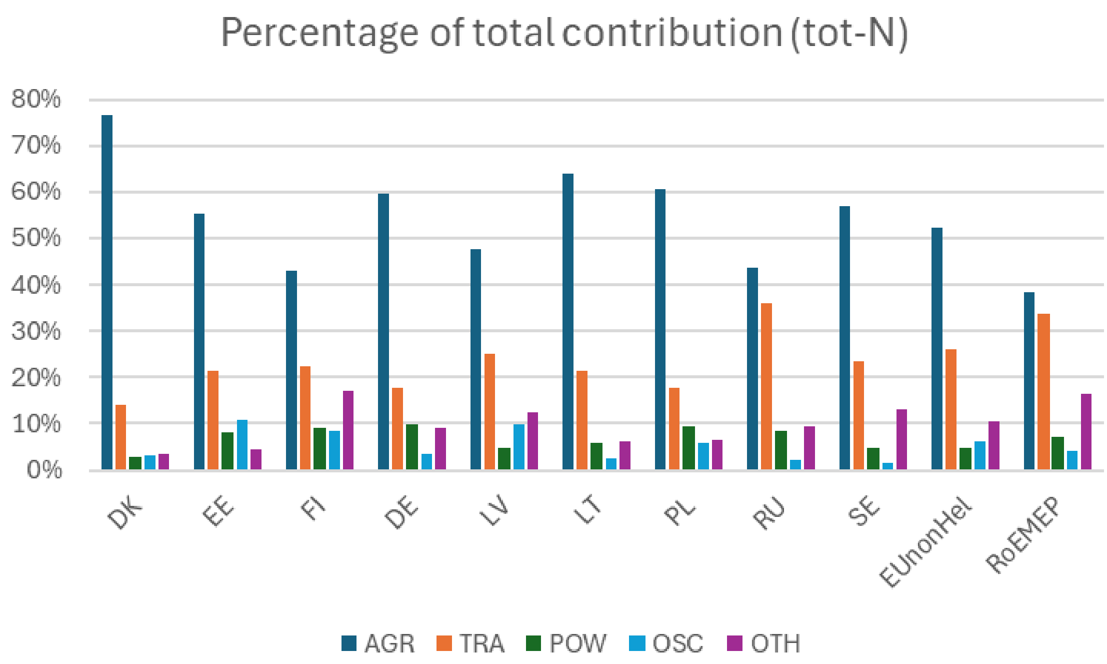


Figure 15. Percentage contribution made by each sector to the country's/region's total contribution to total nitrogen deposition in the Baltic Sea in 2021. For each country/region, the 5 bars sum up to 100%, corresponding to the country's/region's total contribution.

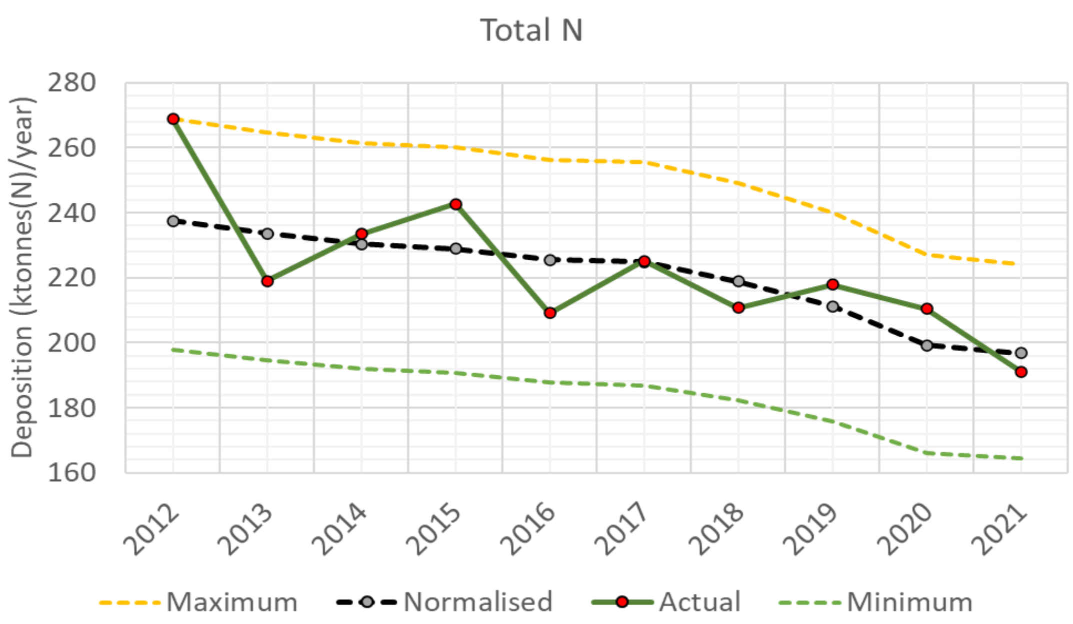


Figure 16. Actual and normalised depositions of total nitrogen, calculated in 2023 for the most recent 10-year period for which data are available. Minimum and maximum values are also shown, depicting what would be the deposition in the most favorable/unfavorable meteorological condition encountered since 1990. The actual value for 2021 corresponds to the value listed in Table 12 (the actual value plotted here for 2017 deviates slightly from the value listed in Table 12 as those calculations were done in 2019 with a different model version and input data).

			Tot-N	Perc.			Tot-N	Perc.
1	DE	AGR	21622	11.3 %	DE	OSC	1296	0.7 %
2	BAS	TRA	17998	9.4 %	EUnonHel	POW	1266	0.7 %
3	PL	AGR	14634	7.7 %	FI	TRA	1228	0.6 %
4	EUnonHel	AGR	13624	7.1 %	LV	AGR	1043	0.5 %
5	DK	AGR	12174	6.4 %	EE	AGR	928	0.5 %
6	RoEMEP	AGR	8205	4.3 %	FI	OTH	928	0.5 %
7	NOS	TRA	7537	3.9 %	RoEMEP	OSC	873	0.5 %
8	RU	AGR	7340	3.8 %	LT	TRA	709	0.4 %
9	RoEMEP	TRA	7201	3.8 %	SE	POW	611	0.3 %
10	SE	AGR	7080	3.7 %	LV	TRA	549	0.3 %
11	EUnonHel	TRA	6758	3.5 %	DK	OTH	534	0.3 %
12	DE	TRA	6437	3.4 %	FI	POW	498	0.3 %
13	RU	TRA	6091	3.2 %	DK	OSC	489	0.3 %
14	PL	TRA	4290	2.2 %	FI	OSC	463	0.2 %
15	DE	POW	3614	1.9 %	DK	POW	447	0.2 %
16	RoEMEP	OTH	3490	1.8 %	RU	OSC	374	0.2 %
17	DE	OTH	3259	1.7 %	EE	TRA	361	0.2 %
18	SE	TRA	2921	1.5 %	LV	OTH	271	0.1 %
19	EUnonHel	OTH	2768	1.4 %	LV	OSC	217	0.1 %
20	FI	AGR	2353	1.2 %	LT	OTH	203	0.1 %
21	PL	POW	2255	1.2 %	LT	POW	187	0.1 %
22	DK	TRA	2239	1.2 %	EE	OSC	181	0.1 %
23	LT	AGR	2102	1.1 %	SE	OSC	177	0.1 %
24	EUnonHel	OSC	1625	0.9 %	EE	POW	139	0.1 %
25	SE	OTH	1620	0.8 %	LV	POW	102	0.1 %
26	RU	OTH	1617	0.8 %	LT	OSC	84	0.0 %
27	PL	OTH	1581	0.8 %	EE	OTH	74	0.0 %
28	RoEMEP	POW	1555	0.8 %				
29	RU	POW	1441	0.8 %				
30	PL	OSC	1412	0.7 %				

Table 13. List of all sources considered in this study, sorted (from largest to smallest) by their contribution to total airborne deposition of total nitrogen in the Baltic Sea in 2021. 'Tot-N': contribution to total nitrogen deposition in the Baltic Sea in 2021 given in tonnes(N), 'Perc.': percentage of total. Example: The Transport sector in Sweden contributed 2921 tonnes(N) to total nitrogen deposition in the Baltic Sea, which was the 18th largest single contribution among the sources considered in this study and corresponds to 1.5% of the total deposition of airborne total nitrogen in the Baltic Sea in 2021. The sum of all percentages listed in this table equals 100% and corresponds to the calculated total annual value of 191.1 ktonnes(N).

BOB			BOS			GUF		
FI	AGR	674	BAS	TRA	1491	RU	AGR	1683
RU	TRA	525	PL	AGR	1261	RU	TRA	1455
BAS	TRA	519	EUnonHel	AGR	1150	BAS	TRA	1398
RU	AGR	450	RoEMEP	AGR	846	RoEMEP	AGR	550
EUnonHel	AGR	368	RoEMEP	TRA	779	RoEMEP	TRA	474
PL	AGR	367	RU	AGR	771	RU	OTH	425
RoEMEP	AGR	332	SE	AGR	771	EUnonHel	AGR	380
RoEMEP	TRA	329	RU	TRA	691	FI	AGR	348
FI	TRA	258	DE	AGR	675	EE	AGR	319
DE	AGR	246	FI	AGR	664	DE	AGR	302
SE	AGR	238	EUnonHel	TRA	540	PL	AGR	301
FI	OTH	229	SE	TRA	484	RU	POW	269
SE	TRA	181	NOS	TRA	458	EUnonHel	TRA	265
EUnonHel	TRA	178	SE	OTH	385	NOS	TRA	255
SE	OTH	164	DE	TRA	338	FI	TRA	240
NOS	TRA	154	RoEMEP	OTH	328	RoEMEP	OTH	217
RoEMEP	OTH	142	PL	TRA	303	SE	AGR	173
RU	OTH	141	FI	TRA	280	DE	TRA	165
RU	POW	134	DK	AGR	216	FI	OTH	158
DE	TRA	125	EUnonHel	OTH	215	SE	TRA	142
FI	OSC	108	FI	OTH	211	PL	TRA	140
PL	TRA	99	DE	POW	208	LT	AGR	136
FI	POW	81	PL	POW	201	EE	TRA	136
DE	POW	81	RU	POW	195	RoEMEP	POW	129
RoEMEP	POW	78	RU	OTH	188	DK	AGR	125
88%			87%			86%		

Table 14. Top 25 contributions to total nitrogen deposition in 2021, listed for each of the nine sub-basins of the Baltic Sea separately. Unit: tonnes(N)/year. The numbers in the bottom row give the percentage of these 25 contributions to the total deposition of reduced nitrogen in the respective sub-basin. The table continues on the next two pages.

GUR			BAP			SOU		
BAS	TRA	716	DE	AGR	11891	DK	AGR	294
RoEMEP	AGR	485	BAS	TRA	10716	DE	AGR	271
RU	AGR	475	PL	AGR	10668	BAS	TRA	180
PL	AGR	472	EUnonHel	AGR	7598	EUnonHel	AGR	159
DE	AGR	396	RoEMEP	AGR	4594	NOS	TRA	99
RU	TRA	394	SE	AGR	4574	SE	AGR	98
EUnonHel	AGR	364	DK	AGR	4531	PL	AGR	82
RoEMEP	TRA	316	DE	TRA	4073	DK	TRA	77
LV	AGR	263	NOS	TRA	4057	DE	TRA	76
LT	AGR	261	EUnonHel	TRA	3882	EUnonHel	TRA	76
EUnonHel	TRA	212	RoEMEP	TRA	3876	RoEMEP	TRA	61
NOS	TRA	206	RU	AGR	3529	RoEMEP	AGR	56
DE	TRA	194	PL	TRA	3099	DE	OTH	43
PL	TRA	181	RU	TRA	2636	DE	POW	42
SE	AGR	179	DE	POW	2266	SE	TRA	36
EE	AGR	169	DE	OTH	2030	EUnonHel	OTH	32
RoEMEP	OTH	150	RoEMEP	OTH	1956	RoEMEP	OTH	30
DK	AGR	132	EUnonHel	OTH	1601	PL	TRA	27
DE	POW	128	SE	TRA	1549	DK	OSC	22
LV	TRA	120	PL	POW	1542	EUnonHel	OSC	18
SE	TRA	99	LT	AGR	1380	DE	OSC	16
RU	POW	95	PL	OTH	1135	DK	OTH	15
DE	OTH	95	DK	TRA	1123	PL	POW	15
PL	POW	88	PL	OSC	978	RU	AGR	14
RU	OTH	85	EUnonHel	OSC	932	EUnonHel	POW	12
85%			91%			96%		

Table 14. Cont'd.

KAT			ARC			WEB		
DK	AGR	3484	BAS	TRA	738	DE	AGR	5680
DE	AGR	1988	EUnonHel	AGR	317	DK	AGR	3237
EUnonHel	AGR	1501	PL	AGR	283	EUnonHel	AGR	1802
BAS	TRA	1247	RoEMEP	AGR	277	NOS	TRA	915
NOS	TRA	1130	FI	AGR	241	BAS	TRA	872
SE	AGR	693	RoEMEP	TRA	224	DE	TRA	803
EUnonHel	TRA	685	RU	TRA	218	EUnonHel	TRA	762
PL	AGR	676	RU	AGR	215	PL	AGR	534
RoEMEP	TRA	613	SE	AGR	204	RoEMEP	TRA	528
RoEMEP	AGR	597	DE	AGR	191	RoEMEP	AGR	475
DE	TRA	562	EUnonHel	TRA	153	DE	OTH	429
DK	TRA	428	NOS	TRA	149	DE	POW	400
DE	OTH	315	SE	TRA	131	DK	TRA	350
DE	POW	312	RoEMEP	OTH	106	EUnonHel	OTH	322
RoEMEP	OTH	303	DE	TRA	98	RoEMEP	OTH	265
EUnonHel	OTH	279	FI	TRA	96	EUnonHel	OSC	171
SE	TRA	231	PL	TRA	93	DE	OSC	159
PL	TRA	197	FI	OTH	84	SE	AGR	157
EUnonHel	OSC	159	DK	AGR	80	PL	TRA	150
RU	AGR	144	LT	AGR	72	EUnonHel	POW	118
DK	OTH	133	DE	POW	64	DK	OSC	96
DE	OSC	120	PL	POW	61	RoEMEP	POW	91
DK	OSC	114	EUnonHel	OTH	61	RU	AGR	91
PL	POW	114	SE	OTH	60	DK	OTH	75
EUnonHel	POW	110	RU	POW	59	PL	POW	74
95%			86%			97%		

Table 14. Cont'd.

4. Conclusions

A sector-wise source-receptor calculation has been performed with the EMEP MSC-W model on EMEP's 0.3° × 0.2° grid regular lon-lat grid for the year 2021. We have calculated the contributions from 13 source countries/regions and 5 selected emission sectors (i.e. 65 country/sector combinations) to depositions of oxidized, reduced and total nitrogen in the Baltic Sea and its 9 sub-basins. Calculations with emissions and meteorological data of the year 2021.

The main conclusions from the study can be formulated as follows:

- The largest contributions to oxidized nitrogen deposition come from the **Transport** sector;
- The Transport sector accounts for about **62%** of oxidized nitrogen deposition in the Baltic Sea;
- The largest contributions to reduced nitrogen deposition come from the **Agriculture** sector;
- The Agriculture sector accounts for about **92%** of reduced nitrogen deposition in the Baltic Sea;
- For total nitrogen deposition, both the Agriculture and Transport sectors make large contributions, accounting for 48% and 34% to total nitrogen deposition, respectively;
- While in 2017, the agricultural sector contributed 107 kt(N), corresponding to 47% of the total nitrogen deposition in 2017 (according to results from the previous project of this kind). In 2021, it contributed 91 kt(N), corresponding to 48% of the total nitrogen deposition in 2021.Thus, although the absolute contribution of the agricultural sector has decreased, its share has increased slightly, because the other sectors have reduced their contributions more;
- The single most important contribution to total nitrogen deposition in the Baltic Sea is made by the Agriculture sector in Germany (accounting for 11.3%), followed by Transport in BAS (i.e. Baltic sea international shipping) accounting for 9.4%, Agriculture in Poland (7.7%), the EUnonHel group of countries (7.1%), and Denmark (6.4%);
- NOx emissions from international shipping in the Baltic Sea and North Sea together cause about 13% of total nitrogen deposition in the Baltic Sea;
- The other three sectors considered in this study (Power generation, Other Stationary Combustion, and all other sectors) account for much less deposition: about one tenth of the total from each of the three sectors, for both oxidized and reduced nitrogen;
- An Excel file containing all source-receptor results is made available along with this report, and files with gridded data (on netCDF format) have been stored and can be made available on request.

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